NBS TECHNICAL NOTE 1197

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Fastest-Mile Wind Speeds in Hurricane Alicia

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E R R A T A   S H E E T

NBS Technical Note 1197
June 1984

Page 21 — Second paragraph, fifth line
"500 m" should read "5 km"

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued June 1984

National Bureau of Standards Technical Note 1197
Natl. Bur. Stand. (U.S.), Tech. Note 1197, 68 pages (June 1984)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1984

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402

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ABSTRACT

Surface wind speeds recorded during the passage of Hurricane Alicia through the Galveston-Houston area on August 18, 1983, are used to estimate fastest-mile wind speeds at 10 m above ground in open terrain. The paper describes the relationships between wind speeds for various averaging times and the boundary-layer representations used in the transformation to fastest-mile speeds. These speeds are compared with wind speeds recommended for the design of buildings and other permanent structures. Errors inherent in the original wind speed records and in the transformations are estimated.

Keywords: Boundary layers; buildings (codes); hurricanes; structural engineering; tropical cyclones; wind speeds.

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1. INTRODUCTION

Although the frequency of hurricane crossings along the Atlantic and Gulf Coasts is approximately 1.8 per year [1], the number of cases where direct and reliable measurements of surface wind speeds over land have been obtained is quite small. Reasons for this lack of reliable data include the sparseness of anemometer sites with unobstructed wind exposure, equipment damage or malfunction, power failures, and, perhaps, a lack of dedicated effort to assemble and analyze wind speed data that have been recorded. Even when reliable records are available, substantial adjustments for nonstandard exposures may be required, employing models based in large part on data obtained in extratropical storms.

There are a number of arguments to support the collection and assessment of wind speed records following a hurricane. First, direct measurements of surface wind speeds aid in the interpretation of data obtained by remote sensing techniques, e.g., radar and satellite. Second, these measurements, along with data obtained from reconnaissance aircraft, provide a means for checking and improving analytical models of hurricanes. Third, reliable estimates of surface wind speeds are essential to the evaluation of the performance of buildings and other structures subjected to loads that approach or exceed the design wind load. Finally, the documentation of surface wind speeds and the transformation of these speeds to standard conditions provide a consistent measure of hurricane intensity. Unfortunately, this has not been done as a matter of course for past hurricanes and there is a tendency to rank hurricanes by wind speed without due regard for the conditions under which those speeds were obtained.

The studies carried out by Reinhold [2] and by Powell [3] following Hurricane Frederic in 1979 appear to represent the most comprehensive collection and analysis of hurricane surface wind speed data to date. Reinhold's results were subsequently applied to the evaluation of structural performance in the region affected by Hurricane Frederic [4]. The motivation for a detailed assessment of surface wind speeds following the passage of Hurricane Alicia through the Galveston-Houston area on August 18, 1983, was to obtain estimates of speeds in the format followed by most building codes, thereby providing a basis for evaluating structural performance. Also, Hurricane Alicia presented an opportunity to evaluate further the procedures used in reference 2 for the transfer of wind speeds to standard conditions.

2. STORM SUMMARY

Hurricane Alicia had its origins in a low-pressure system located approximately 300 km south of New Orleans late on August 14. The system moved slowly to the west over the next 2 days and was designated a tropical storm on August 15. This designation was upgraded to a hurricane at 2200 hours[1] on August 16, at which time the center of the storm system was located approximately 270 km southeast of Galveston, moving to the west-northwest. Hurricane Alicia continued on a west-northwest heading over the next 24 hours. This heading shifted to the north-northwest early on August 18 when Alicia was approximately 110 km south-southeast of Galveston. Alicia came ashore near the southwest tip of Galveston Island at about 0730 hours on August 18, passing to the southwest of Alvin, Texas at 1030 hours and over the western section of Houston

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[1] Unless otherwise noted, all times refer to GMT. Note that CST = GMT - 6.

from 1230 to 1400 hours. The track shown in figure 1 represents a composite of a storm track prepared by Lambeth [5] and information assembled and interpreted by Golden [6]. Figure 1 will probably be subject to some revision as more information becomes available through the analysis of barometric pressure records and radar data.

The lowest barometric pressure officially recorded over land was 28.55 inches Hg (966.7 mb) at the National Weather Service office at Alvin. An unusual feature of this hurricane was an outer convective band, principally in the northeast quadrant, which produced surface wind speeds as high or higher than those near the eyewall. This band was clearly visible on radar and, for a number of anemometer sites to the northeast of the storm track, appeared on the wind speed records as a double peak. This double peak was also observed at one anemometer site on the southwest (left) side of the storm track. Estimates of eye diameter, based on radar data, range from 30 to 35 km [7]. Transit time through the Galveston-Houston area was approximately 8 hours and the average translation speed was about 15 km/hr.

3. WIND SPEED RECORDS AND SITE CHARACTERISTICS

Copies of stripchart records and daily records of surface weather observations were obtained from a number of sources during a visit by the author to the affected area from August 29 to September 1, 1983. In many cases it was possible to make a first-hand assessment of the wind exposure and instrumentation. This information was later supplemented by topographic maps and, in some cases, photographs. Records from other sites became available during the course of this study, usually with only a cursory description of the wind exposure and instrumentation.

There were 17 sites in all from which useful information was obtained. Some of the wind speed records were automatically recorded, and others were manually logged. Site locations are indicated on figure 1 using the numbering sequence of table 1 which lists the anemometer height, assumed roughness length, type of anemometer, and type of observation.

The following site descriptions provide the information required for the transfer of wind speeds to standard conditions. Consistent with reference 2, standard conditions are taken to mean a height of 10 m above flat, open terrain of sufficient extent to allow full development of an equilibrium boundary layer. The corresponding terrain roughness is characterized by a roughness length parameter, z_o, which is taken to be 0.05 m. Wind speeds and barometric pressure are reported in the units of the original observations (1 knot ≃ 0.51 m/s; 1 mph ≃ 0.45 m/s; 1 inch = 25.4 mm). Consistent with standard practice, barometric pressure is expressed simply as "inches" rather than "inches Hg."

USCGC Buttonwood (Site 1)

The Coast Guard Cutter Buttonwood was berthed at the U.S. Coast Guard Station in Galveston during the passage of Hurricane Alicia. The station is located on the northeast tip of Galveston Island adjacent to Old Fort San Jacinto and faces Galveston Channel to the west. Hourly and special observations of sustained speeds and peak gusts were obtained from a propeller-vane anemometer mounted 13.7 m above the water. Wind speed data provided by the Buttonwood cover the period 1800 hours on August 17 to 2100 hours on August 18.

Peak gusts of 110 and 105 knots were observed at 0730 and 1000 hours, respectively. The maximum sustained speed (visually averaged over 1 minute)

of 83 knots was observed at 1000 hours from a direction of 210 degrees. Wind direction shifted clockwise from 45 degrees at 0000 hours to 205 degrees at 1700 hours. The maximum rate of shift occurred at 0730 hours. The minimum barometric pressure was 29.27 inches at 0945 hours.

For wind direction of 45 to 170 degrees the fetch consists of very smooth and open terrain extending approximately 2.7 km from the station to the Gulf of Mexico. From 170 to 230 degrees, the overland fetch includes the central business district and dock area of Galveston (approximately 6.4 km) followed by about 2.4 km of open water along Galveston Channel. No other ships were berthed or moored near the Buttonwood and there are no major buildings or other obstructions that would have altered the wind field significantly. In converting the wind speeds observed by the Buttonwood to open exposure, a uniform roughness length of z_o = 0.01 m was assumed.

NWS Galveston (Site 2)

The National Weather Service wind instrumentation is mounted on a mast located on top of City Hall on Rosenberg Avenue in the central business district. Anemometer height is 32 m above street level. A continuous record covering the period from 1200 hours on August 17 to 0100 hours on August 19 was obtained from a Mod. F-420 C anemometer. Hourly observations of sustained speed and peak gust were also recorded. Due to an equipment malfunction, wind direction was not recorded other than by entry of quadrant in the daily record. It was necessary, therefore, to rely on observations of wind direction made by USCGC Buttonwood which was berthed approximately 4.5 km northeast of City Hall.

Peak gusts of 89 and 82 knots were recorded at 0634 and 0919 hours, respectively, on August 18. The highest hourly mean speed of 50.3 knots occurred between 0900 and 1000 hours with a corresponding wind direction of approximately 220 degrees. Minimum barometric pressure was 29.22 inches at 0900 hours.

Because of the limited wind fetch over the central business district, the boundary layer at the anemometer site was assumed to be in transition and the transfer of wind speeds to open terrain was carried out using the procedure described in section 4.2.

For the wind direction corresponding to the highest speeds recorded (approximately 220 degrees), a fetch of 4 km and a roughness length of z_o = 1.5 m was assumed for the central business district. A correction for zero plane displacement (the height above ground level at which the wind speed effectively becomes zero), z_d = 5 m, was also applied. Upwind of the central business district the boundary layer was assumed to be fully developed over relatively open terrain with a roughness length of z_o = 0.15 m.

<u>TCAAMN-AQM 4</u> (Site 3)

This site is located on the seawall that runs north-south along the east side of Texas City. The site has a clear exposure to Galveston Bay for wind directions in the north-to-southeast sector. Anemometer height is 10 m. The site is part of the Texas City Ambient Air Monitoring Network and wind speeds are recorded as hourly mean speeds by a digital data logging system. Due to a power failure the last wind speed entry was made at 0400 hours on August 18, at which time the hourly mean speed was 52.5 mph. The corresponding wind direction

was 65 degrees. A roughness length z_o = 0.005 m was assumed in the transfer of wind speeds to open terrain.

TCAAMN-Met 5 (Site 4)

This site is also operated by the Texas City Ambient Air Monitoring Network and is located in the northeast corner of the Amoco refinery complex near 20th Street and 5th Avenue, S. The meteorological tower is instrumented at two levels (10 and 90 m) and wind speed and direction are recorded as both 10 minute sequential averages and hourly means by a digital data logging system. The anemometers are 3-cup, fast response units. As with site AQM 4, this site was also affected by a power failure and no data were recorded after 0600 hours on August 18.

Maximum 10 minute mean speeds were 38.9 and 73.0 mph at the 10 and 90 m levels, respectively. For the period 0000 to 0600 hours, wind direction at the 10 m level shifted clockwise from 35 to 80 degrees. The corresponding shift at the 90 m level was from 30 to 60 degrees. Barometric pressure at the time of power failure was 29.47 inches.

The wind exposure for the final 2 hours of record involved a long fetch over Galveston Bay, followed by a fetch of approximately 3.2 km over the central business district of Texas City and three to four city blocks of residential area with numerous trees. In the analysis, a roughness length z_o = 0.005 m was assumed for the over-water fetch and z_o = 1.0 m over land. A correction of 2 m was applied to the anemometer heights to account for zero plane displacement. A detailed description of the analysis of data for this site is given in section 4.2.

Dow Plant A - Freeport (Site 5)

Plant A of Dow Chemical USA is located on the north bank of the Old Brazos River directly east of Freeport. The anemometer site has a relatively open exposure and is located approximately 1.6 km west-northwest of Plant A and 4 km from the Gulf of Mexico. It was not possible to visit this site, but the anemometer was described as being mounted on a mast on top of a one-story building at a height of approximately 10 m. The stripchart record for this site covers the period 2300 hours on August 17 to 1500 hours on August 18.

The wind speed record indicates two distinct peaks with a peak gust of 87 mph at 0816 hours and a second peak of 83 mph at 0956 hours. Wind direction shifted counterclockwise from 360 degrees at 0000 hours to 220 degrees at 1500 hours. Barometric pressure was not reported.

The wind fetch includes the city of Freeport for directions between 290 and 220 degrees. Over this same range of direction the length of urban exposure varies from 1.3 to 1.0 km with fairly open terrain between the city and the anemometer site ranging from 2.4 down to 0.8 km. In the transfer of wind speeds to open terrain, a uniform roughness length of $z_o = 0.15$ m was assumed.

Dow Plant B - Freeport (Site 6)

Plant B of Dow Chemical USA is located on the north bank of the Brazos River approximately 8 km west-northwest of Plant A. The anemometer at this site is a propeller-vane and is mounted on a mast on top of a two-story building at the east entrance to the plant. The height of the anemometer was estimated to be 13 m. The stripchart record for this site covers the period 2300 hours on August 17 to 1600 hours on August 18.

The peak gust recorded at this site was 94 mph at 0731 hours with a corresponding wind direction of 295 degrees. The wind direction shifted counterclockwise from 360 degrees at 0000 hours to 215 degrees at 1500 hours. Maximum rate of shift occurred at approximately 0700 hours. The minimum barometric pressure was reported to be 28.53 inches at 0600 hours.

Because of the proximity of the chemical plant, adjustments were made to account for profile transition using the approach described in section 4.2. The assumptions made regarding surface roughness and wind fetch are summarized in table 2.

CBAAMN - Amoco (Site 7)

The meteorological tower operated by the Chocolate Bayou Ambient Air Monitoring Network is located between the Amoco and Monsanto chemical plants on Chocolate Bayou, just west of Route 2004 and approximately 40 km west of Galveston. Anemometers are mounted at the 10 and 90 m levels and 1 hour averages of wind speed and direction are recorded by a digital data logging system. Due to a power failure no data were recorded after 0500 hours on August 18. Hourly mean wind speeds logged at 0400 hours were 38.6 and 50.0 mph at the 10 and 90 m levels, respectively. The terrain surrounding the Chocolate Bayou site is very flat and open. Estimates of surface roughness based on average speeds at the 10 and 90 m levels suggest $z_o \simeq 0.01$ m. Barometric pressure during the last hour of record averaged 29.49 inches.

NWS Alvin (Site 8)

Alvin, Texas is approximately 40 km south-southeast of the Houston central business district and 45 km west-northwest of Galveston. The National Weather Service facility is located on Route 6, 2.5 km east of town. The anemometer

is a Mod. F-420 C mounted on a 10 m mast. The surrounding terrain is flat and fairly open with a few isolated buildings and trees. The stripchart record obtained from NWS covers the period 2000 hours on August 17 to 1900 hours on August 18. Wind direction was not recorded.

The wind speed record clearly indicates passage of the eye at 1025 hours. Peak gusts before and after eye passage were 63 knots at 0742 hours and 62 knots at 1136 hours. Minimum barometric pressure was 28.55 inches at 1025 hours.

A uniform roughness length of $z_o = 0.20$ m was used in the conversion of hourly mean speeds to fastest-mile speeds at 10 m in open terrain. This roughness length appears high based on a purely subjective assessment of the wind exposure, but it is somewhat low when compared with the gust ratios obtained from the wind record. The analysis of this record is discussed in section 4.1.

Ellington Air Force Base (Site 9)

Ellington AFB is located approximately 25 km southeast of the Houston central business district and 15 km inland from Galveston Bay. Hourly and special observations of sustained speeds and peak gusts were obtained from a propeller-vane anemometer located adjacent to the main runway. Anemometer height is approximately 4 m. Observations used in this analysis covered the period 0630 to 1700 hours on August 18.

Peak gusts of 64 and 69 knots were observed at 0755 and 1337 hours, respectively, and the maximum sustained speed was 48 knots at 0755 and at 1255 hours. Wind direction shifted clockwise from 40 to 180 degrees with the maximum

rate of shift occurring at approximately 1130 hours. The minimum barometric pressure of 29.00 inches was observed at 1155 hours.

The upwind terrain for the directions of interest is flat and open with the nearest development located approximately 5 km to the southeast. A uniform roughness length $z_o = 0.10$ m was assumed in the wind speed analysis.

Hobby Airport (Site 10)

William P. Hobby Airport (formerly known as Houston International Airport) is located 15 km southeast of the Houston central business district and 12 km west-northwest of Ellington AFB. Records of regularly scheduled and special surface weather observations made by FAA Flight Services and obtained from the National Climatic Data Center are incomplete for Hobby Airport due to a power interruption from 0600 to 1400 hours on August 18. The last hourly observation prior to power failure was taken at 0450 hours, indicating a sustained speed of 25 knots from 50 degrees and gusts to 40 knots. The next observation was taken at 1419 hours with a sustained speed of 37 knots from 190 degrees and gusts to 56 knots. The peak gust for the hour was 68 knots at 1446 hours. The anemometer is a Mod. F-420 C and its height was reported to be 6.1 m. The anemometer location is approximately midfield.

Additional unofficial observations of wind speeds at Hobby Airport were obtained by a member of the FAA staff who was on duty in the control tower during the passage of Alicia. The control tower receives wind speed and direction data from the anemometer location just described. Although the top floor of the control tower was evacuated during the period of highest winds, speed and direction were observed at irregular intervals. These observations are summarized in table 3 and are discussed further in section 5.1.

Because the area surrounding Hobby Airport is relatively well developed with numerous trees, a uniform roughness length of $z_o = 0.15$ m was assumed in the transfer of wind speeds to open terrain.

Exxon-Baytown (Site 11)

This site is located on the west side of Baytown and is approximately 35 km due east of the Houston central business district. Continuous records of wind speed and direction were obtained from a propeller-vane anemometer mounted on a 36.6 m mast located near the center of the Exxon refinery complex. Records provided by Exxon Company USA cover the period 2000 hours on August 17 to 0500 hours on August 19.

The wind speed recorder contains three pens with full-scale ranges of 0-50, 0-100, and 0-200 mph, respectively. Although each pen has a different color, overlap of the records made it very difficult to identify peak gusts during the period of highest winds, in particular from 0930 to 1600 hours on August 18. However, it was possible to estimate 30 minute mean speeds for the entire length of record. A second recorder provides a moving time average (time constant ≃ 1 minute) of wind speed at full-scale ranges of 0-50 and 0-200 mph. This second recorder indicated some problems with intermittent loss of signal and its stripchart was not used in the analysis reported herein. Circuit diagrams for the recording system indicate an analog conversion of anemometer output to correspond to a height of 30 ft (9.1 m). Based on a comparison with other records available in the Baytown area before and after the passage of Alicia, it does not appear that the anemometer output was subjected to any modification and it has been assumed in this analysis that the wind speeds recorded on the stripcharts do, in fact, correspond to the actual speeds at

the 36.6 m level. Rainfall, tide data, and barometric pressure were also recorded.

The highest 30 minute mean speed was 70 mph, which occurred three times between 1130 and 1500 hours on August 18. The corresponding wind direction ranged from 95 to 140 degrees. The highest 1 minute average appears to have been 76 mph at 1220 hours and several gusts above 110 mph were recorded between 1130 and 1430 hours on August 18. Directional data prior to 0900 hours on August 18 are missing, but the remainder of the record indicates a clockwise shift from 75 degrees at 0900 hours to 145 degrees at 2000 hours on August 18. Maximum rate of shift occurred between 1200 and 1230 hours. Minimum barometric pressure was 29.44 inches at 1200 hours.

Because of the large and abrupt variations in surface roughness surrounding the site, adjustments had to be made to account for boundary layer transition. Assumptions regarding surface roughness, zero plane displacement, and length of fetch are summarized in table 4.

<u>U.S. Industrial Chemicals</u> (Site 12)

This site is located on the west side of Galveston Bay, approximately 30 km east of the Houston central business district and 7 km west-southwest of the Exxon refinery at Baytown. Both wind speed and direction were recorded by stripchart and the record covers the period 0630 to 1700 hours on August 18. The recorder is of the dot-printing type and the quality of the record made it impossible to estimate gust speeds. However, 15 minute averages were extracted for use in the wind speed analysis. Anemometer height was reported to be 30 ft (9.1 m) [5] and a uniform roughness length of z_o = 0.2 m was assumed in the transfer of speeds to open terrain.

The maximum 15 minute average speed was 59 mph at 1100 to 1115 hours and wind direction over the length of record ranged from 80 to 190 degrees. The wind shift was clockwise with the maximum rate of shift occurring at approximately 1130 hours. Barometric pressure was not reported.

USCGC Clamp (Site 13)

The Coast Guard Cutter Clamp was berthed at Greens Bayou near the Houston Ship Channel during the passage of Hurricane Alicia. This location is 19 km due east of the Houston central business district. Hourly and special observations of sustained speeds and peak gusts were obtained from a propeller-vane anemometer mounted at a height of 10.7 m. Wind speed data obtained from the Clamp cover the period 0600 to 2000 hours on August 18.

A peak gust of 104 knots was observed at 1200 hours and the highest sustained speed of 55 knots was observed at 1400 hours. The corresponding directions were 80 and 135 degrees. The wind shift was clockwise and changed from 045 degrees at 0600 hours to 190 degrees at 2000 hours. Maximum rate of shift occurred at 1330 hours. The minimum barometric pressure of 29.11 inches was observed at 1230 hours.

The site at Greens Bayou was not visited, but it is understood that the Clamp had a clear exposure to the maximum winds. Based on recent maps showing commercial development in the area, a uniform roughness length of z_o = 0.20 m was assumed.

USCGC Hatchet (Site 14)

The Coast Guard Cutter Hatchet was moored at Greens Bayou on August 18, and hourly observations were obtained for the period 0600 to 2200 hours. Observed speeds and directions exhibit considerable scatter from 1300 to 1800

hours and this data set was not used in this study. The peak gust reported by Hatchet was 107 knots at 1115 hours. Minimum barometric pressure was 29.10 inches at 1200 hours.

Houston Health Department (Site 15)

The Houston Health Department maintains a wind recording station at 1115 N. MacGregor, approximately 5.5 km south-southwest of the central business district. The anemometer is mounted close to the roof of the penthouse on a multistory building, about 23 m above street level. Stripchart records of wind speed and direction were obtained for the period 0800 to 1700 hours on August 18 and it is clear from the low mean speeds and high gust ratios that the anemometer was severely obstructed by the building on which it is mounted. It is doubtful whether any meaningful information can be extracted from this wind speed record without resorting to a wind tunnel model study.

The wind direction at this site ranged from 30 to 200 degrees. The wind shift was clockwise with the maximum rate of shift occuring at 1300 to 1330 hours. Barometric pressure was not reported.

Braes Meadow (Site 16)

This record was obtained at a private residence located approximately 17 km southwest of the Houston central business district. The anemometer height is approximately 6.7 m and the surrounding area is residential development with single-story houses and numerous trees close to the height of the anemometer. The recorder is of the dot-printing type and, as was the case for the US Industrial Chemicals record, it was not possible to extract gust speed data. However, it was possible to estimate 15 minute wind speeds which indicated a

maximum of 24 mph between 1100 and 1200 hours on August 18. Wind direction was not recorded.

The wind speed data suggest passage of the eye at 1300 to 1400 hours. Barometric pressure was continuously recorded with a minimum pressure of 28.86 inches occurring at 1300 hours. Problems encountered with the analysis of the Braes Meadow data are discussed in section 5.1.

Houston Intercontinental Airport (Site 17)

Houston Intercontinental Airport (IAH) is located approximately 25 km north of the Houston central business district. Stripchart records of wind speed provided by the National Weather Service cover the period from 2300 hours on August 17 to 0100 hours on August 19. The recording was interrupted by a power failure from 1130 to 1230 hours on August 18. Hourly and special observations of sustained speed, peak gust and direction were also obtained at IAH. The anemometer is a Mod. F-420 C and is mounted at a height of 6.1 m with an open exposure.

In contrast with most other stations located to the northeast of the storm track, the wind record at IAH exhibits only one clear peak. The highest gust was 68 knots at 1346 hours. Maximum sustained speed obtained from the hourly observations was 44 knots at 1353 hours and the corresponding wind direction was 80 degrees. The wind direction shifted clockwise from 50 degrees at 0100 hours to 180 degrees at 2000 hours. Maximum rate of shift occurred at approximately 1430 hours. A uniform roughness length of $z_o = 0.10$ m was assumed. The analysis of records for IAH is described in detail in section 4.1.

4.0 ANALYSIS OF WIND SPEED RECORDS

The transformation of observed wind speeds to fastest-mile speeds at 10 m above flat, open terrain makes use of representations of the atmospheric boundary layer that are based upon mean wind speeds averaged over a period of approximately 1 hour. As the observed speeds correspond to various averaging times, they are converted to hourly mean speeds prior to applying adjustments for anemometer height and terrain roughness. The hourly mean speeds so adjusted are then converted to fastest-mile speeds, i.e., speeds based upon the time required for the passage of a volume of air with a longitudinal dimension of 1 mile.

4.1 ESTABLISHED FLOW REGIMES

The approach used herein to estimate wind speeds corresponding to standard conditions has been described by Reinhold [2] and is based in large part on procedures developed by Simiu and Scanlan [8]. Briefly, the wind speeds actually observed at the anemometer sites are converted to hourly mean speeds using the relationship:

$$U_t(z) = U_{hr}(z) \left[1 + \frac{0.98\ c(t)}{\ell n(z/z_o)}\right] \tag{1}$$

where $U_t(z)$ is the maximum mean wind speed at height z averaged over t seconds, $U_{hr}(z)$ is the corresponding hourly mean speed, c(t) is a coefficient that depends on t and on the longitudinal component of turbulence, z is the height of the anemometer, and z_o is the roughness length corresponding to the terrain upwind of the anemometer site. Figure 2 gives values of c(t) that are consistent with gust ratios reported by Durst [9] for open terrain conditions. Wind speed records obtained in fully established flows over surfaces of uniform roughness suggest that equation 1 and the values of c(t) in figure 2 are applicable to

roughness lengths of up to $z_o = 1.0$ m [8]. For roughness lengths greater than $z_o = 1.0$ m, larger values of $c(t)$ may be appropriate.

The choice of t in equation 1 depends upon the type of wind speed record obtained at the site. If stripcharts are available, the hourly mean speed can be estimated from sequential time averages (usually 10 or 15 minutes) without resorting to equation 1. Alternatively, the peak gust within the hour can be used with the assumption that the associated averaging time for most mechanical anemometer/recorder systems is approximately 2 seconds.

Many stations record only the sustained speed which is mentally averaged by the observer over a period of approximately 1 minute. It is usual for those observations to be made within the last 10 minutes of each hour, although special observations may be made more frequently. Since the sustained speeds entered in the record are not necessarily the maximum sustained speeds within the hour, an adjustment is required prior to estimating U_{hr}. This is done by converting the hourly observation of sustained speed, U_s, to the extreme fastest-mile speed, U_{fm}, within the hour using the empirical relationship:

$$U_{fm}(z) = 9.55 + 0.999\, U_s(z) \tag{2}$$

which has been suggested by Thom [10] based on the analysis of records obtained under strong-wind conditions. The corresponding averaging time for U_{fm} is $t = 3600/U_{fm}$. The hourly mean speed then is obtained using equation 1.

The transfer of hourly mean speeds at the anemometer site to standard height ($z = 10$ m) in open terrain ($z_o = 0.05$ m) is accomplished using the relationship developed in reference 8,

$$\overline{U}(10) = U_{hr}(z) \frac{\ell n\,(\frac{10}{0.05})}{\ell n\,(\frac{z}{z_o})} \left(\frac{0.05}{z_o} \right)^{0.0706} \tag{3}$$

where $\overline{U}(10)$ is the hourly mean speed at 10 m in open terrain and z and z_o are the anemometer height and roughness length, respectively, at the anemometer site. To make a direct comparison with basic design wind speeds presented in standards such as ANSI A58.1 [11], $\overline{U}(10)$ is transformed to an equivalent fastest-mile wind speed using equation 1. Because the averaging time, t, depends upon the value of U_{fm}, this last step requires an iterative solution of equation 1.

Wind speed observations made over a 20-hour period at Houston Intercontinental Airport (IAH) are used to demonstrate the procedure just outlined. As noted in section 3.0, both stripchart records and hourly observations of sustained speed were obtained at IAH. Anemometer height is 6.1 m and the exposure is uniform and reasonably open for all directions. Hourly mean speeds, U_{hr}, at z = 6.1 m are based on visual estimates of the time-averaged speed for each 10 minute segment of the stripchart within the hour. The maximum value of U_{600} within the hour is plotted against U_{hr} in figure 3. Equation 1 is also plotted on figure 3 for three values of z_o. The maximum value of U_2 within the hour is plotted against U_{hr} in figure 4, along with equation 1 for the same three values of z_o. Equation 1 is not particularly sensitive to the choice of z_o for averaging times of 10 minutes or longer. For t = 2 seconds the data suggest z_o = 0.1 m at the higher wind speeds.

Estimates of the maximum sustained wind speeds, U_{60}, are plotted against the corresponding hourly mean speeds in figure 5. To obtain U_{60}, the hourly observations of U_s were converted to U_{fm} using equation 2 and U_{60} was then obtained from equation 1. In making this transformation it was assumed that z_o = 0.1 m. It appears that equation 2 overestimates U_{fm} (and thus U_{60}) at the lower speeds, but the corresponding values of U_{60} appear to be consistent with z_o = 0.1 m at the highest speeds. This is not surprising given the

form of equation 2 and the fact that it is based on the analysis of maximum speeds within a storm. Assuming that the hourly observations of sustained speed do in fact correspond to 1 minute averages, the uncertainty involved in estimating U_{hr} from U_s would be about the same as that involved in estimating U_{hr} from U_2. Once U_{hr} has been established, equations 3 and 1 are used to obtain $\overline{U}(10)$ and U_{fm}, respectively, for standard height and open terrain.

Results of an analysis similar to that just described are shown on figures 6 and 7 for NWS Alvin. The wind exposure is reasonably uniform and a roughness length of z_o = 0.2 m was selected based on a subjective assessment of the terrain roughness. Anemometer height is 10 m. Wind speed data are limited to a stripchart record and no hourly observations of sustained speeds were made.

The data for NWS Alvin exhibit much more scatter at the higher speeds than do the data for IAH. This may be due in part to the isolated buildings and slightly rougher terrain at Alvin. However, it is important to note that the edge of the eyewall passed over the station and the wind characteristics at Alvin were likely quite different from those at IAH. The gust speeds plotted in figure 7 suggest a roughness length greater than z_o = 0.2 m, but this is not consistent with the local terrain. Estimates of U_{hr} taken directly from the stripchart are believed to be at least as reliable as those for IAH.

4.2 TRANSITION ZONES

The procedure used to estimate wind speeds in fully established flow regimes must be modified where changes in terrain roughness do not allow the boundary layer to reach full equilibrium at the anemometer site. This is usually the case for anemometers located in an industrial complex or in a

downtown area. Methods for dealing with this situation have been the subject of a number of papers, e.g., references 12 and 13. However, the validation of these methods is based in large part on wind tunnel test results or on measurements in full-scale where the roughness lengths were typically less than 0.1 m. The procedure used here is developed in reference 14 and has been shown to be consistent with roughness lengths of the order of $z_o = 1$ m.

For a smooth-to-rough transition the characteristics of the smooth terrain (equilibrium) boundary layer are assumed to be preserved above a height $\delta = X/12.5$ where X is the distance downwind from the roughness change. Below this height the mean velocity profile is assumed to be logarithmic and continuous with the undisturbed profile at height δ. For $X \geq 500$ m, the boundary layer is assumed to be fully developed and in equilibrium with the rougher terrain. Upwind of the roughness change and for $z \geq \delta$ downwind of the roughness change we have the relationship:

$$\frac{U_{hr}(z, z_o')}{U_{hr}(10, z_o')} = C(z) = \frac{\ln\left(\frac{z}{z_o'}\right)}{\ln\left(\frac{10}{z_o'}\right)} \tag{4}$$

where z_o' is the upwind (smooth terrain) roughness length. Downwind of the change from z_o' to z_o (smooth-to-rough) and for $z < \delta$ the relationship:

$$\frac{U_{hr}(z, z_o)}{U_{hr}(10, z_o')} = C(\delta)\,\frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{\delta}{z_o}\right)} \tag{5}$$

is assumed to apply.

Wind speed data from two sites at Texas City provide a means of checking the consistency of the approach just outlined. The two sites, AQM 4 and Met 5, have been described in section 3.0. The wind speed records cover the period 0700 hours on August 17 to 0600 hours (0400 hours for AQM 4) on August 18 and consist of hourly mean speeds logged by a digital data system. Unfortunately, the records were terminated by a power failure about 2 hours before the speeds reached their maximum. Wind direction for the period of record ranged from 45 to 75 degrees which is approximately along the alignment of AQM 4 - Met 5. The wind fetch between AQM 4 and Met 5 includes the central business district of Texas City and a short segment of residential area with numerous trees and bushes.

Hourly mean speeds at the 10 and 90 m levels at Met 5 are plotted against the corresponding speeds at AQM 4 in figures 8 and 9. Speeds at the two sites are highly correlated and there appears to be a shift in the wind regime beginning at about 1800 hours (1200 hours CST) on August 17.

In the analysis a roughness length of $z_o' = 0.005$ m was assumed for the wind fetch over Galveston Bay. Between AQM 4 and Met 5, the value of z_o = 1.0 m was assumed and, because of houses and trees near Met 5, an adjustment for zero plane displacement $z_d = 2.0$ m was applied to equation 5. Height of the nonequilibrium or inner boundary layer was taken to be 256 m as suggested by the relation $\delta = X/12.5$

The transformation of $U_{hr}(10, z_o)$ at Met 5 to $U_{hr}(10, z_o')$ using equation 5 gives $U_{hr}(10, z_o') = 1.87\ U_{hr}(10, z_o)$. The corresponding transformation for the 90 m level at Met 5 gives $U_{hr}(10, z_o') = 0.87\ U_{hr}(90, z_o)$. The transformation of $U_{hr}(10, z_o)$ is in good agreement with the relationship indicated in figure 8. The transformation of $U_{hr}(90, z_o)$ underestimates

$U_{hr}(10,z_o')$ by approximately 10 percent. The choice of z_o = 1.0 m for the wind fetch between AQM 4 and Met 5 is consistent with the roughness lengths suggested in reference 14. However, the relatively good agreement between AQM 4 and the 10 m level at Met 5 is effected by the adjustment for zero plane displacement. The data at the 90 m level of Met 5 suggests that δ should be increased slightly and that a better estimate might be provided by $\delta = X/10$.

4.3 ESTIMATION ERRORS

The errors involved with estimating fastest-mile wind speeds in open terrain from wind speed records obtained from various sites involve three general types of errors: (1) observation errors; (2) site characterization errors; and (3) modeling errors.

1. Observation Errors

Observation errors include faulty speed measurements due to mechanical and/or electrical problems with the anemometer and recording system; errors in equipment calibration; and human error in making and logging observations. Government agencies such as NWS, FAA, and USCG, and many private firms that make routine meteorological measurements maintain quality assurance programs that include periodic equipment calibration and observer certification. The typical accuracy of a mechanical anemometer and stripchart recorder would be $\pm$ 1 mph up to 30 mph and $\pm$ 3 percent above 30 mph. Observer errors are more difficult to quantify, but are probably less than 5 percent in the case of sustained speeds and about 1 to 2 mph for peak gusts. Errors involving untrained observers would be higher, particularly in the case of sustained wind speeds which require a subjective assessment on the part of the observer.

Additional observation errors are involved with the analysis of stripchart records. If the stripchart has a reasonably open scale (chart speed ≈ 75 mm/hr and dynamic range ≈ 100 mm), errors in extracting peak gust data, U_2, are probably no larger than $\pm$ 1 mph. Errors of $\pm$ 3 percent in estimating U_t, where $10 \leq t \leq 30$ minutes, can be expected. These errors tend to be systematic rather than random and, therefore, errors associated with estimating U_{hr} on the basis of U_t are of approximately the same magnitude.

2. Site Characterization Errors

Site characterization errors arise from uncertainties in anemometer height, the effect of local obstructions such as buildings and trees, the effective roughness length and wind fetch for the terrain in the immediate vicinity of the site, and changes in terrain roughness upwind of the site. At some sites the density of local obstructions may be high enough to require an adjustment for zero plane displacement.

Standard anemometer heights are usually specified by the agency making the meteorological measurements. For heights of 10 m or less, expected deviations would be 0.5 m or less. For nonstandard heights greater than 10 m, it is likely that errors in estimating heights would not exceed the smaller of 5 percent or 2 meters.

Although the effects of local obstructions may become apparent with changes in wind direction, they are not necessarily obvious from a wind speed record alone. These effects can be very difficult to quantify without resorting to special studies. Wind speed records from such sites are usually of limited value, although the directional data may be fairly reliable. With regard to roughness length, various terrain categories have been defined and subjectively

described, based on numerous studies carried out on equilibrium boundary layers. For reasonably uniform terrain it is doubtful that the assumed roughness length would differ from the true roughness length by more than x 2 for $z_o < 0.1$ m and, perhaps, by no more than x 1.5 for $z_o \geq 0.1$ m. The greatest uncertainties arise with rough exposures where it becomes difficult to differentiate between local obstructions, roughness length, and zero plane displacement. Also, relatively few reliable studies have been carried out on equilibrium boundary layers developed over rough terrain, e.g., $z_o > 1$ m. The problem is compounded where there are abrupt and significant changes in the terrain roughness that produce a transition boundary layer. In some cases the only alternative is to discount the value of the wind speed record.

3. Modeling Errors

Modeling errors result from the use of mathematical representations of wind speed that depart from the true wind speed characteristics at a given site. For the most part, validation of the relationships presented in sections 4.1 and 4.2 has been carried out in extratropical storms and their validity for hurricane winds is uncertain. A possible limitation on equation 1 for large roughness lengths has already been noted in section 4.1. Based on full-scale measurements summarized in reference 14, equation 3 may underestimate $\overline{U}(10)$ by about 3 percent for $z_o \simeq 0.3$ m and by about 10 percent for $z_o \simeq 1.5$ m. A modified expression for $\overline{U}(10)$ is developed in reference 14, based on full-scale measurements, and is shown in reference 15 to be in very close agreement with actual measurements of hurricane winds retarded by water-to-land transitions.

4.4 PROBABLE RANGE OF ERROR IN ESTIMATES OF WIND SPEEDS

With the information given in section 4.3, it is possible to establish a range of error associated with estimates of U_{fm} at a given site. For the case of U_{600} at IAH, the range of observation errors (equipment and stripchart analysis) would be about 4 percent. Since these errors tend to be systematic, they would also apply to estimates of U_{hr}. Errors in estimating $\overline{U}(10)$ from U_{hr} using equation 3 would result from incorrect anemometer height, incorrect choice of roughness length, and incorrect functional form of equation 3 as discussed in section 4.3. Underestimating z by 0.5 m would overestimate $\overline{U}(10)$ by about 2 percent. If the true roughness length were z_o = 0.05 m, the choice of z_o = 0.1 m would overestimate $\overline{U}(10)$ by about 11 percent. The error due to the functional form of equation 3 is believed to be negligible for the conditions at IAH. If these errors are assumed to be uncorrelated, the range of error in estimating $\overline{U}(10)$ from the stripchart record would be about $\pm$ 12 percent, using standard error analysis. From this it is seen that uncertainties with regard to the roughness length are by far the most significant.

If U_{hr} is estimated on the basis of either U_2 or U_{60}, the range of scatter for IAH is about $\pm$ 5 percent at the highest speeds and substantially more at the intermediate speeds as can be seen from figures 4 and 5. Assuming that the other sources of error are unchanged, the range of error in estimating $\overline{U}(10)$ at IAH on the basis of U_2 or U_{60} would be about $\pm$ 14 percent.

In the case of NWS Alvin, the range of scatter for U_2 vs U_{hr} is about $\pm$ 10 percent at the highest speeds as can be seen from figure 7. Accounting for observation and site characterization errors, the range of error in estimating $\overline{U}(10)$ on the basis of U_2 would be about $\pm$ 16 percent.

Roughness lengths at IAH and at NWS Alvin are relatively small compared with roughness lengths at, for example, Exxon-Baytown (see table 4). Overestimating any one of the roughness parameters (z_o', z_o, or z_d) will lead to an overestimate of $\overline{U}(10)$. If the true characterization of the Exxon-Baytown site were $z_o' = 0.20$ m, $z_o = 1.0$ m, and $z_d = 1.5$ m, use of the roughness parameters in table 4 would overestimate $\overline{U}(10)$ by about 8 percent. Assuming the roughness parameters are either all overestimated or all underestimated, and accounting for observation errors and the uncertainty in anemometer height, the corresponding range of error in estimating $\overline{U}(10)$ would be about $\pm$ 10 percent. To this must be added the error resulting from incorrect fetch length and from modeling errors, estimated to be about 2 and 8 percent, respectively. Thus, the range of error associated with estimates of $\overline{U}(10)$ at Exxon-Baytown is about $\pm$ 13 percent. The reported anemometer height at Exxon-Baytown is 36.6 m. Errors in estimating the roughness parameters would become more significant at lower anemometer heights.

Errors discussed up to this point apply to estimates of $\overline{U}(10)$. Estimates of U_{fm} involve an additional error whose magnitude depends upon the degree to which equation 1 represents the true relationship between U_{fm} and $\overline{U}(10)$. Unfortunately, none of the records obtained during the passage of Hurricane Alicia permits a direct comparison of observed U_{fm} with $\overline{U}(10)$ for standard height and wind exposure. However, it is possible to place some bounds on the estimation error associated with equation 1 by examining the variation of U_{600}/U_{hr} and U_2/U_{hr} for those sites approximating standard conditions. Three such sites having open-scale stripcharts are IAH, NWS Alvin, and Dow Plant A. Recall that data for U_{600} and U_2 are plotted in figures 3 and 4 for IAH and in figures 6 and 7 for NWS Alvin.

Using the site characteristics listed in table 1, the ratios of U_{600}/U_{hr} obtained by use of equation 1 are 1.07, 1.07, and 1.08 for IAH, NWS Alvin, and Dow Plant A, respectively. Based on the total length of record at each site, the corresponding measured ratios of U_{600}/U_{hr} average 1.11, 1.09, and 1.07. The coefficients of variation are 0.05, 0.06, and 0.04, respectively. Ratios of U_2/U_{hr} obtained by use of equation 1 are 1.69, 1.68, and 1.73 for IAH, NWS Alvin, and Dow Plant A, respectively. The corresponding measured ratios are 1.85, 1.69, and 1.84. The corresponding coefficients of variation are 0.11, 0.10, and 0.08.

Averaging times associated with the estimated fastest-mile speeds at these three sites range from 40 to 140 seconds. In view of the differences between predicted and measured values of U_{600}/U_{hr} and U_2/U_{hr} just described, and given that both z and z_o are specified for standard conditions, it is reasonable to expect that estimates of U_{fm} based on $\overline{U}(10)$ in equation 1 will involve a mean error of about $\pm$ 3 percent. The coefficient of variation for $U_{fm}/\overline{U}(10)$ would be about 0.08. For U_{fm} = 70 mph, this would correspond to a standard deviation of about 6 mph.

To summarize the errors associated with the estimation of fastest-mile wind speeds, observation errors are believed to be of the order of $\pm$ 4 percent while errors of $\pm$ 10 percent can be expected from uncertainties with respect to site characterization. When combined with modeling errors, estimates of U_{fm} can be expected to have a range of error of about $\pm$ 12 percent when derived from stripchart records, and about $\pm$ 16 percent when derived from hourly observations.

5.0 FASTEST-MILE SPEEDS FOR STANDARD HEIGHT AND EXPOSURE

Using the approach outlined in section 4.0, the hourly mean speeds, $U_{hr}(z, z_o)$, were converted to equivalent fastest-mile speeds for standard height ($z = 10$ m) and open terrain ($z_o = 0.05$ m). The results are presented in figures 10 to 24. For those sites where the hourly mean speed was extracted from a stripchart record, successive 1 hour intervals used in the analysis overlap by 1/2 hour. Thus, any two successive estimates of U_{hr} are not independent. The estimates of U_{fm} are plotted at the midpoint of the corresponding 1 hour interval. For those sites where the record consists only of hourly observations of sustained speed, the corresponding estimates of U_{fm} are plotted at the time of observation. Wind direction is also plotted for those sites where directional data were available. Some records exhibit data gaps or were terminated due to power failures before passage of the eye. Extreme fastest-mile speeds for the sites considered in this study are listed in table 5.

5.1 PROBLEMS ENCOUNTERED AT INDIVIDUAL SITES

A general description of each site, types of wind speed records obtained, and the assumptions made regarding wind fetch, roughness length, and corrections made for zero plane displacement have been addressed in section 3.0. Table 6 rates the anemometer sites in terms of relative reliability of wind speed estimates. This assessment is necessarily subjective and is based on the type of wind speed record available, the complexity of the terrain at the anemometer site, the proximity of buildings and other obstructions, and the height adjustment required. Because of problems encountered with the data analysis and interpretation of results, two of the anemometer sites deserve additional comment.

Hobby Airport

As was noted in section 3.0, a power failure caused an 8 hour gap in the hourly surface weather observations made by FAA Flight Services. Unfortunately, this gap corresponds to the closest approach of the eye to Hobby Airport. The unofficial observations made by the control tower staff partially cover this gap and these observations have been summarized in table 3.

Estimates of U_{fm} based on sustained wind speeds of table 3 exhibit much more scatter than do the estimates based on peak gusts. This is consistent with the subjective nature of sustained speed measurements and the unambiguous definition of peak gust. Therefore, the estimates of U_{fm} derived from control tower data and plotted on figure 18 are based on gust speeds.

Where the control tower and Flight Services data overlap (approximately 1400 to 2000 hours), there appears to be a time lag of 1 hour or more in the control tower data. Referring to table 3, the wind shift was observed at approximately 1530 hours while figure 1 suggests 1200 to 1230 hours for wind shift. Although there are uncertainties with regard to the true storm track, the time marks for 1100 and 1300 hours in figure 1 can be established with some confidence based on the data sets for NWS Alvin, Houston Health Department, and Braes Meadow. Also, the observation at 1300 hours indicates an eye position to the south of Hobby Airport when, in fact, the eye was very close to Houston Health Department and Braes Meadow. Thus, there is good reason to believe that the first three observations in table 3 should be plotted 2 to 3 hours earlier in figure 18, and the last two observations 1 to 2 hours earlier. This does not alter the validity of the wind speed estimates.

Braes Meadow

Because of the difficulty in assessing the effects of local terrain and obstructions on the wind speeds recorded at Braes Meadow, no attempt was made to make a direct transfer to open terrain. The approach used was to examine the relationship between U_{900} at Braes Meadow and U_S at Hobby Airport over a 15 hour interval beginning at 0900 hours on August 17, well in advance of the eye passage. Wind direction at Hobby Airport ranged from 30 to 80 degrees during this interval. The two sets of data are plotted in figure 25 with the 15 minute intervals at Braes Meadow selected to coincide with the hourly observations at Hobby Airport. The relationship suggested by this limited data set is:

$$U_{900} \text{ (Braes Meadow, mph)} \simeq 0.4\, U_S \text{ (Hobby, knots)} \qquad (6)$$

Estimates of U_{fm} for Braes Meadow were then obtained using the site characteristics for Hobby Airport as described in section 3.0. Because of the very substantial corrections involved with using this approach, the wind speeds plotted in figure 23 must be viewed with some skepticism and it is reasonable to expect errors of the order of 15 to 20 percent.

5.2 DISTRIBUTION OF FASTEST-MILE WIND SPEEDS

With reference to table 5, the higher values of U_{fm} estimated for USCGC Buttonwood and NWS Galveston range from 86 to 91 mph. To the northwest at Exxon-Baytown and U.S. Industrial Chemicals, U_{fm} ranges from 92 to 100 mph. All of these stations are located approximately the same distance from the storm track (45 km) and, with the exception of U.S. Industrial Chemicals, each site exhibits a double peak in the wind speed record. In each case the time differential for first and second peaks is approximately 3 hours. The

time lag for corresponding peaks at Galveston and Baytown is approximately 4 hours, in good agreement with the hurricane translation time indicated on figure 1. It seems clear that the maximum speeds at these sites to the right of the storm track are associated with an outer convective band, as noted in section 2.0.

Compared with Galveston, there is no discernible attenuation of wind speeds in the Baytown area; in fact, the speeds at Baytown are slightly higher. Galveston Bay appears to have a considerable influence on the windfield to the right of the storm track.

Ellington AFB, Hobby Airport, and USCGC Clamp are also located to the right of the storm track, but at distances ranging from 15 to 30 km. While these sites do not exhibit the clear double peaks noted above, the period over which the highest peaks occurred at each site is approximately 5 hours. Note that the times indicated for Hobby Airport control tower observations are believed to be in error as discussed in section 5.1. The range of peak speeds for these three sites is 67 to 84 mph with some indication that the speeds increase slightly with distance from the storm track. Again, this suggests the influence of an outer convective band.

Dow Plants A and B at Freeport are located approximately 25 km to the left of the storm track, and although they are within 6 km of each other, only Plant A exhibits a clear double peak. Based on Texas A & M radar data, Powell suggests that the peaks observed at both sites at approximately 0800 hours are due to passage of the eyewall while the second peak at plant A is associated with the intense portion of an outer convective band [7]. The peak speeds range from 74 to 84 mph and reflect the retardation due to surface shear over land. The peak speeds at Freeport lag those at Galveston by approximately 30 minutes, in

reasonable agreement with their locations relative to the storm track shown in figure 1.

The peak speeds listed for NWS Alvin in table 5 do not correspond to passage of the eyewall as can be seen from figure 16. At the eyewall the values of U_{fm} range from 59 to 63 mph while the highest value of U_{fm} is 64 mph, occurring 1-1/2 hours after passage of the eyewall. The time history of passage at Alvin is highly symmetric about the center of the eye and again suggests the influence of an outer convective band. What is most surprising about the record at Alvin is the relatively low speeds when compared with other sites with substantial overland wind fetch such as Hobby Airport and the sites at Freeport. Also the peak speed at Braes Meadow, which is believed to have experienced eye passage, is substantially higher (87 mph), even taking into account the uncertainty that must be attached to the Braes Meadow record.

The last site affected by Hurricane Alicia for which reliable data are available is IAH. The record indicates only one clear peak of 74 mph at 1330 hours. However, the stripchart record was interrupted by a power failure from 1130 to 1230 hours and the hourly observations suggest that a lesser peak occurred at about 1230 hours. This site is located approximately 25 km to the right of the storm track and is probably the best indicator of wind speed attenuation as Hurricane Alicia moved inland. Taking 89 mph as an average peak value for the Galveston area, the attenuation factor for Galveston-IAH is about 0.8. The translation distance is about 95 km.

5.3 COMPARISON OF U_{fm} WITH RECOMMENDED DESIGN SPEEDS

As was pointed out in section 1.0, part of the motivation for this study was the estimation of wind speeds in a format that could be compared with

wind speeds recommended for the design of buildings and other permanent structures, thereby providing a basis for evaluating structural performance. The basis for this comparison is the fastest-mile speed at a height of 10 m in open terrain (z_o = 0.05 m) that has an annual probability of being exceeded equal to 0.02 (50 year mean recurrence interval). Reference 11 denotes this as the "basic wind speed" and, for the Galveston-Houston area, indicates basic wind speeds of approximately 100 mph at the coastline and 90 mph inland at Houston.

Table 7 is based on the storm track shown in figure 1, the estimated fastest-mile speeds plotted in figures 10 to 24, and the distribution of peak speeds discussed in section 5.2. While the resolution of basic wind speeds in table 7 is probably not justified, it appears that wind speeds produced by the passage of Hurricane Alicia exceeded the design wind speeds recommended in reference 11 only in the Baytown-La Porte area and, possibly, near the southwest end of Galveston Island where no wind speed measurements were obtained. It would appear, therefore, that Hurricane Alicia was an event that one would expect to occur once each 50 years or so on the average.

6.0 SUMMARY AND CONCLUSIONS

Wind records obtained from 17 anemometer sites that experienced strong winds during the passage of Hurricane Alicia through the Galveston-Houston area on August 18 are analyzed. Results of this analysis are expressed as fastest-mile wind speeds at a height of 10 m in open terrain (z_o = 0.05 m). Of the original 17 sites, two sites were rejected because of unreliable wind speed data and one site was considered to be suspect because of the large wind speed corrections required. Three sites had their records terminated by power fail-

ures prior to the onset of maximum winds and two sites had their records interrupted by power failures. Thirteen of the sites yielded estimates of fastest-mile wind speeds that are believed to be of medium to high reliability.

Observations and conclusions reached during the course of this study are summarized below:

1. Hurricane Alicia made landfall near the southwest tip of Galveston Island at approximately 0730 hours on August 18.
2. The path of Hurricane Alicia through the Galveston-Houston area was generally on a line from SW Galveston Island -- Chocolate Bayou -- Alvin -- SW Houston -- NW Houston.
3. Transit time of the eye through the Galveston-Houston area was about 8 hours with a corresponding speed of translation of 15 km/hr.
4. Eye diameter at landfall was approximately 30 km, based on radar data.
5. The lowest barometric pressure officially recorded during the overland phase of Hurricane Alicia was 28.55 inches Hg. at NWS Alvin. This pressure was recorded at 1025 hours on August 18.
6. Several anemometer sites registered a double peak in the wind record. This double peak correlates well with outer convective bands observed on radar images.
7. The range of error in estimating fastest-mile wind speeds, U_{fm}, from stripchart records is believed to be about $\pm$ 12 percent. When hourly observations of sustained speed are the basis for the estimate, the range of error can be as large as $\pm$ 16 percent.
8. Site characterization errors are typically $\pm$ 10 percent and are by far the most significant component of the estimation errors.

9. Relationships used herein to calculate hourly mean and fastest-mile speeds appear to be reliable for terrain of moderate roughness ($z_0 \leq 0.20$ m). However, additional studies are needed for rough terrain and for wind exposures with abrupt and significant changes in roughness length.

10. Estimates of extreme fastest-mile wind speeds for standard conditions ranged from 100 mph at the Exxon refinery at Baytown to 64 mph at NWS Alvin. The fastest-mile speeds are believed to have been in the range 80-85 mph near the Houston central business district.

11. A comparison of estimated fastest-mile wind speeds with design speeds recommended by ANSI Standard A58.1-1982 suggests that only in the Baytown-La Porte area and, possibly, near the west end of Galveston Island were the recommended design speeds exceeded.

12. The mean recurrence interval associated with Hurricane Alicia is believed to be about 50 years.

7.0 ACKNOWLEDGMENTS

The success of studies such as the one reported herein is highly dependent upon the interest and support of those who contribute to the collection of storm data. Among those who contributed to the documentation of Hurricane Alicia are: Steve Harned of WSO Houston, Bill Blum of WSO Galveston, Kenneth Hill and James Maple of Exxon Company USA, Charles Rice of Amoco Oil Company, Harry Walker of Monsanto, W. Smith of Dow Chemical USA, Lt. John Allen and QMC Michael Martin of USCG Group Galveston, David Burrows of FAA, MSgt. Larry Franklin of 111th Weather Flt USAF, Jimmy O'Donnel of Houston, Lyman Cox of Charter International Oil Co., and R. L. Abshier of Houston Lighting and Power.

For their assistance in providing critical information and for their helpful comments and suggestions, special thanks are due Joseph Golden of ERL/NOAA, Mark Powell of AOML/HRD/NOAA, and Ahsan Kareem of the University of Houston.

Appendix I -- References

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Appendix II -- Notation

$c(t)$ = Coefficient

t = Time in seconds

$U_{hr}(z)$ = Hourly mean speed at height z

$U_s(z)$ = Sustained speed at height z

$U_t(z)$ = Maximum mean speed at height z averaged over t seconds

$\overline{U}(10)$ = Hourly mean speed at 10 m in open terrain

U_{fm} = Fastest-mile wind speed

z = Height above ground

z_o = Roughness length

z_o' = Roughness length for smooth terrain in smooth-to-rough transition

δ = Depth of nonequilibrium boundary layer

Table 1. Characteristics of Anemometer Sites

	Anemometer Site	Anemometer Ht. (m)	Assumed z_o (m)	Type of Instrument	Wind Speed Record: Stripchart	Peak Gust	Sustained	10-min Avg.	1-hr Avg.	Direction	Remarks
1	USCGC Buttonwood	13.7	0.01	Propeller-vane		✓	✓			✓	
2	NWS Galveston	32	1.5(1)	Mod. F-420 C	✓	✓	✓				Direction vane not operating. Anemometer assumed to be in transition zone.
3	TCAAMN - AQM 4	10	0.005						✓	✓	Record terminated by power failure at 0400 hours.
4	TCAAMN - Met 5	10,90	1.0(1)	3-cup fast responae				✓	✓	✓	Anemometer aasumed to be in transition zone. Record terminated by power failure at 0600 hours.
5	Dow A - Freeport	≈ 10	0.15		✓					✓	
6	Dow B - Freeport	≈ 13	0.40(1)	Propeller-vane	✓					✓	Anemometer assumed to be in transition zone.
7	CBAAMN-Amoco	10,90	0.02	3-cup fast responae					✓	✓	Record terminated by power failure at 0500 hours.
8	NWS Alvin	10	0.20	Mod. F-420 C	✓						Wind direction not recorded.
9	Ellington AFB	4	0.10	Propeller-vane		✓	✓			✓	
10	Hobby Airport	6.1	0.15	Mod. F-420 C		✓	✓			✓	Record interrupted by power failure from 0600 to 1400 hours.
11	Exxon-Baytown	36.6	1.5(1)	Propeller-vane	✓		✓			✓	Anemometer aasumed to be in transition zone.
12	US Induatrial Chemicals	9.1	0.20		✓					✓	
13	USCGC Clamp	10.7	0.20	Propeller-vane		✓	✓			✓	
14	USCGC Hatchet	10.7	0.20	Propeller-vane		✓				✓	Record conaidered unreliable.
15	Houston Health Dept.	≈ 23	----(1)		✓					✓	Record conaidered unreliable.
16	Braes Meadow	≈ 6.7	----(1)	3-cup	✓						Record of questionable reliability. Wind direction not recorded.
17	Houaton Intercontinental Airport (IAH)	6.1	0.10	Mod. F-420 C	✓	✓	✓			✓	Record interrupted by power failure from 1130 to 1230 hours.

Notes: (1) See aection 3.0 for aite description.

1 ft = 0.3048 m

Table 2. Estimated Terrain Roughness at Dow Plant B

Wind Direction (Deg)	z_o' (Upwind of Change) (m)	z_o (Downwind of Change) (m)	z_d (m)	Length of z_o Fetch (km)
$325 \leq \theta \leq 360$	0.20	0.20	0	>5
$230 \leq \theta < 325$	0.15	0.40	2	2.5
$\theta < 230$	0.05	0.40	2	1.0

1 ft = 0.3048 m

Table 3. Observations Reported from Hobby Airport Control Tower August 18, 1983.

CDT	GMT	Sustained Speed (knots)	Peak Gust (knots)	Direction (deg)	Barometric Pressure (inches Hg.)
0545	1045	64	73	60	29.82
0800(1)	1300	82	93	90	28.81
1030(2)	1530	58-63	89	180	28.81
1300	1800	50	60-65	---	-----
1350	1850	28	37-39	---	29.90

Notes: (1) Eye reported to be approaching Pearland-Friendswood area.

(2) Wind shift at approximately this time.

1 knot ≃ 0.51 m/s.

1 inch = 25.4 mm.

Table 4. Estimated Terrain Roughness at Exxon-Baytown

Wind Direction (Deg)	z_0' (Upwind of Change) (m)	z_0 (Downwind of Change) (m)	z_d (m)	Length of z_0 Fetch (km)
$75 < \theta \leq 95$	0.30	1.5	3	2.1
$95 < \theta < 125$	Sudden wind shift in this sector			
$125 \leq \theta \leq 150$	0.20	1.5	3	1.0

1 ft = 0.3048 m

Table 5. U_{fm} for Standard Height and Open Terrain
(z = 10 m, z_o = 0.05 m)

		First Peak			Second Peak		
	Anemometer Site	U_{fm} (mph)	Direction (deg)	Time (GMT)	U_{fm} (mph)	Direction (deg)	Time (GMT)
1	USCGC Buttonwood	86	120	0700	91	210	1000
2	NWS Galveston	88	---(1)	0700	89	---	0930
3	TCAAMN - AQM 4	65	75	0530(2)	—	---	----
4	TCAAMN - Met 5 (10 m) TCAAMN - Met 5 (90 m)	65 58	80 60	0530(2) 0530(2)	— —	--- ---	---- ----
5	Dow A - Freeport	84	280	0730	74	240	1000
6	Dow B - Freeport	83	300	0730	—	---	----
7	CBAAMN-Amoco (10 m) CBAAMN-Amoco (90 m)	44 40	45 50	0430(2) 0330(2)	— —	--- ---	---- ----
8	NWS Alvin	59	--(1)	0730	64	---	1330
9	Ellington AFB	84	40	0800	84	150	1300
10	Hobby Airport	82	90	1300(3)	67	200	1500
11	Exxon-Baytown	100	90	1130	93	140	1430
12	US Industrial Chemicals	92	125	1100	—	---	----
13	USCGC Clamp	77	40	0800	84	135	1400
14	USCGC Hatchet	(4)					
15	Houston Health Dept.	(4)					
16	Braes Meadow	87(5)	---(1)	1130	56(5)	---	1530
17	Houston Intercontinental Airport (IAH)	74	80	1330(3)	—	---	----

Notes: (1) Wind direction not recorded.

(2) Record terminated by power failure.

(3) Record interrupted by power failure.

(4) Record considered unreliable.

(5) Record of questionable reliability.

1 mph ≈ 0.45 m/s.

Table 6. Relative Reliability of Estimates of U_{fm}

High	Medium	Low
USCGC Buttonwood	NWS Galveston	Hobby Airport
TCAAMN-AQM 4	TCAAMN-Met 5	USCGC Hatchet
Dow A	Dow B	Houston Health Dept.
CBAAMN-Amoco	Exxon-Baytown	Braes Meadow
NWS Alvin	USCGC Clamp	
Ellington AFB		
US Industrial Chemicals		
IAH		

Table 7. Comparison of Extreme Fastest-Mile Wind Speeds with Recommended Design Speeds

Region	Estimated Range of U_{fm} (mph)	Basic Wind Speed (Ref. 11) (mph)
Freeport-Angleton	80-85	95-100
Galveston-Texas City	85-90	98
Baytown-La Porte	95-100	95
Greens Bayou-Deer Park	85-95	95
Alvin-Pearland	65-80	95
Pasadena-Houston	80-85	90-95
NW Houston	75-80	85-90

1 mph ≃ 0.45 m/s.

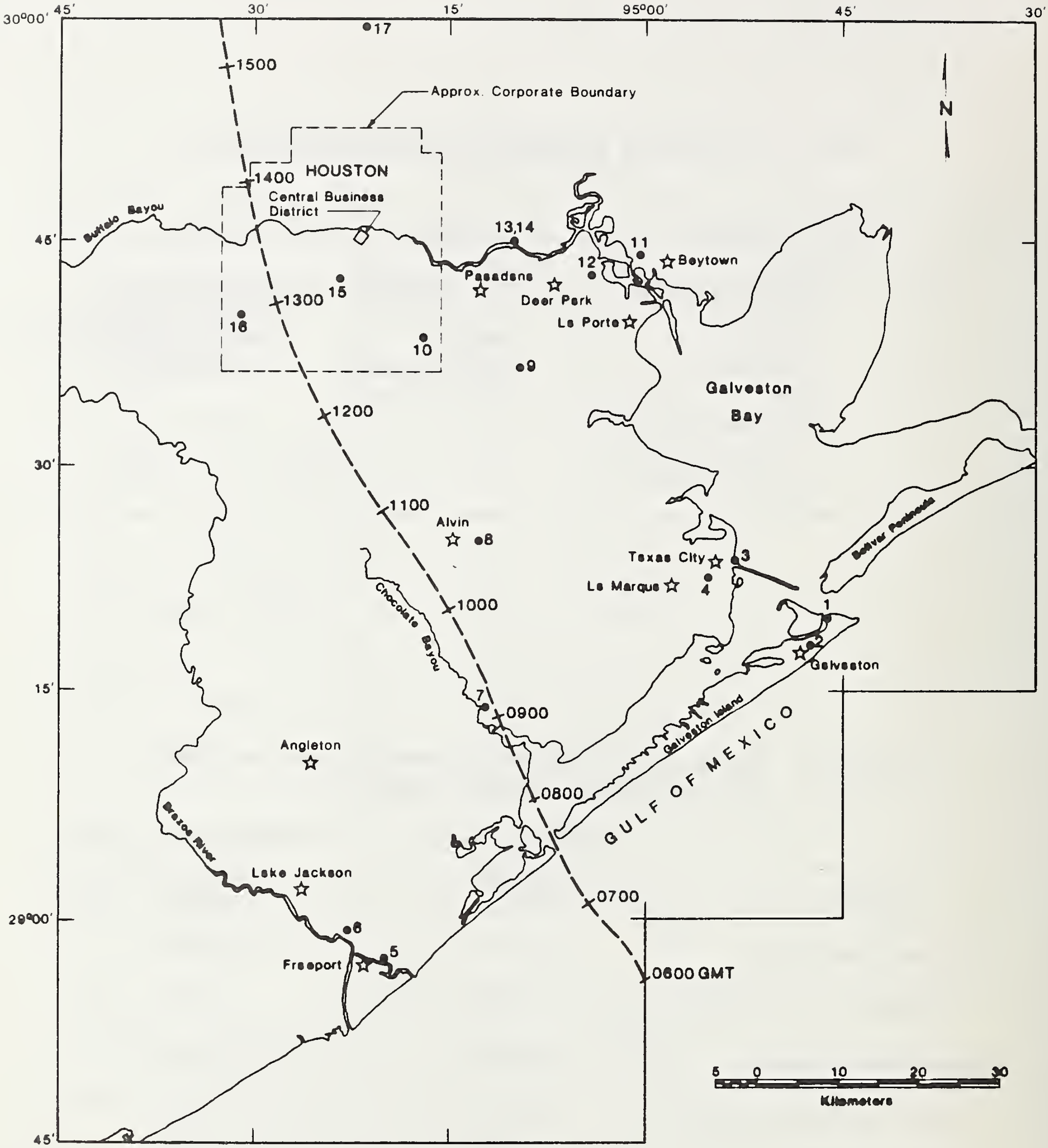

Figure 1. Location map and hurricane track

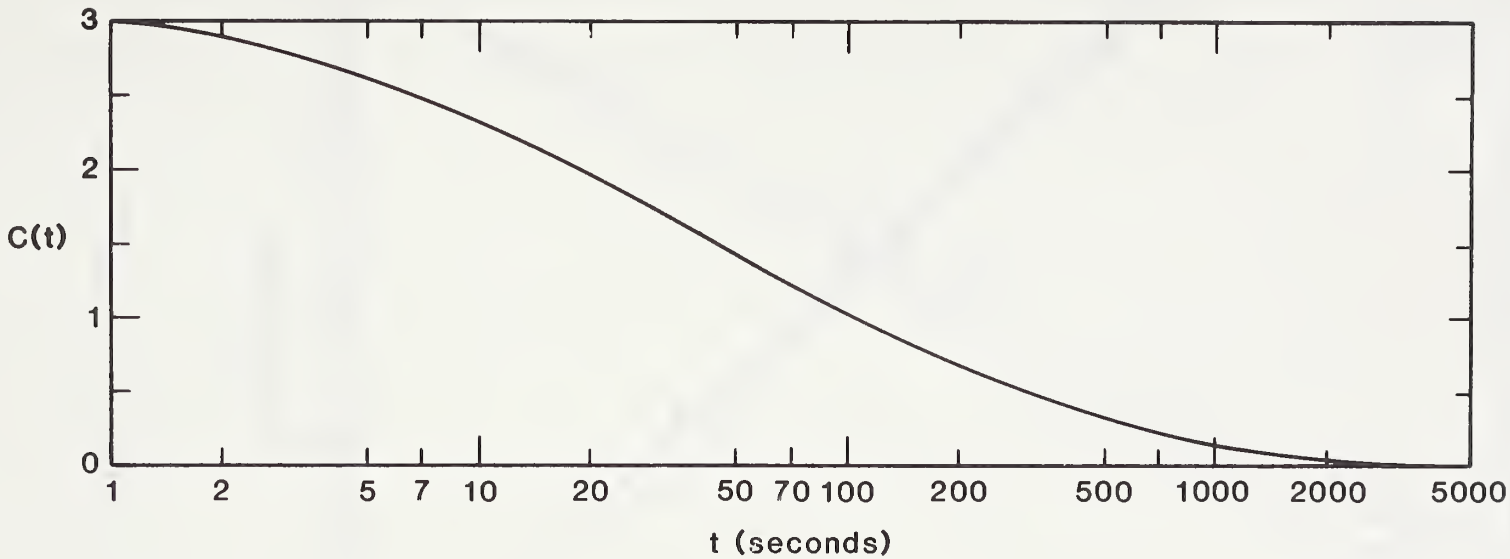

Figure 2. Plot of c(t)

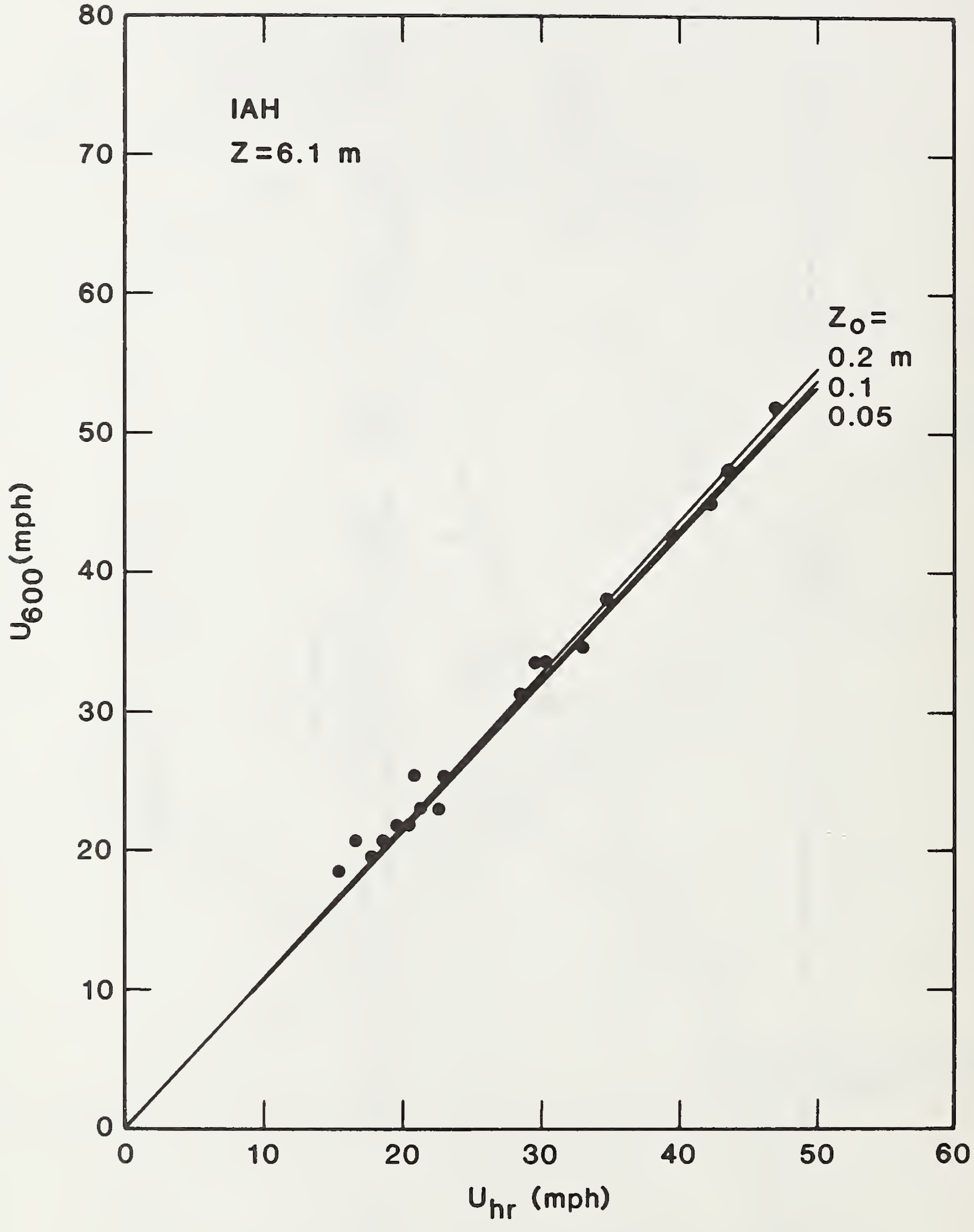

Figure 3. U_{600} vs U_{hr} at IAH

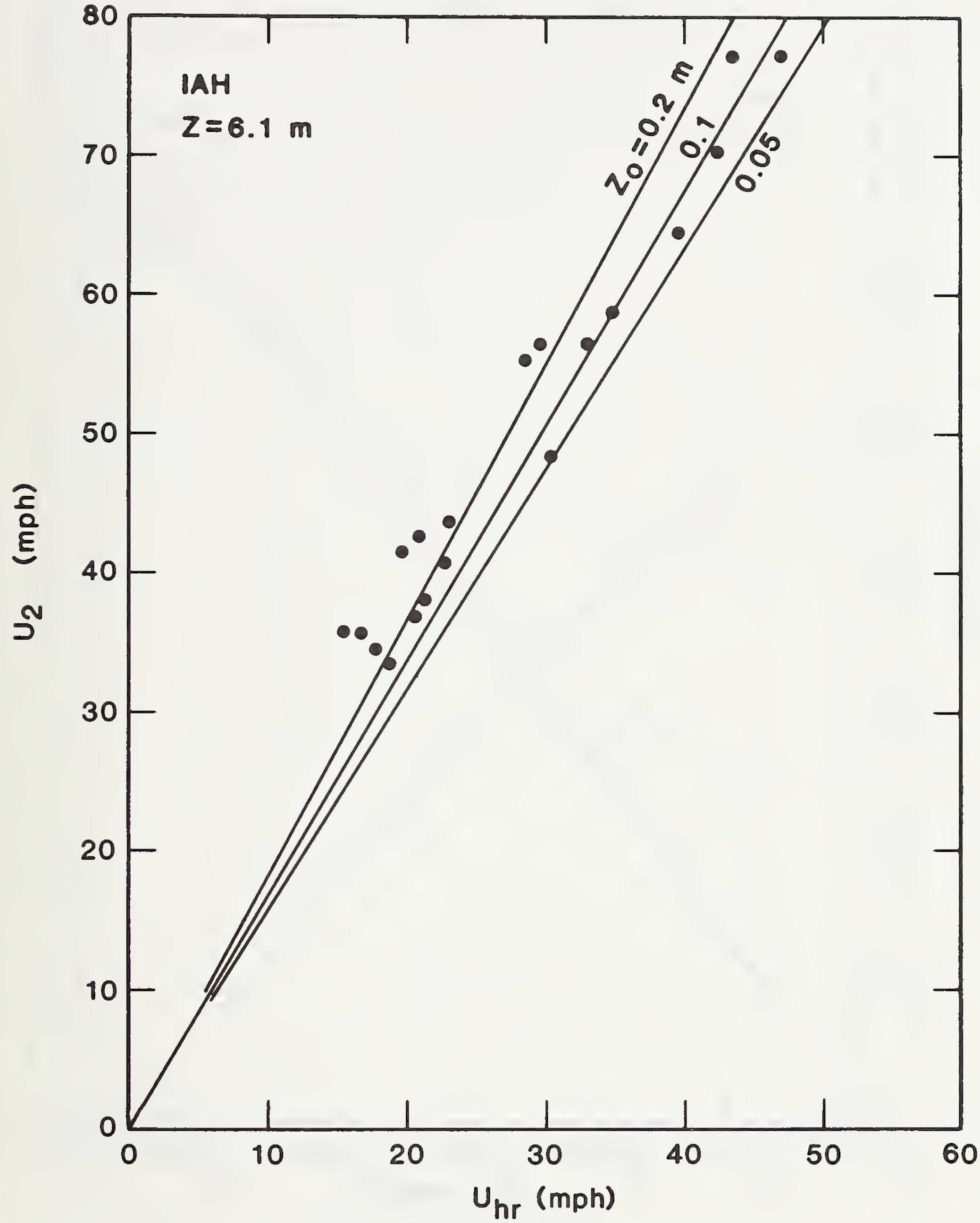

Figure 4. U_2 vs U_{hr} at IAH

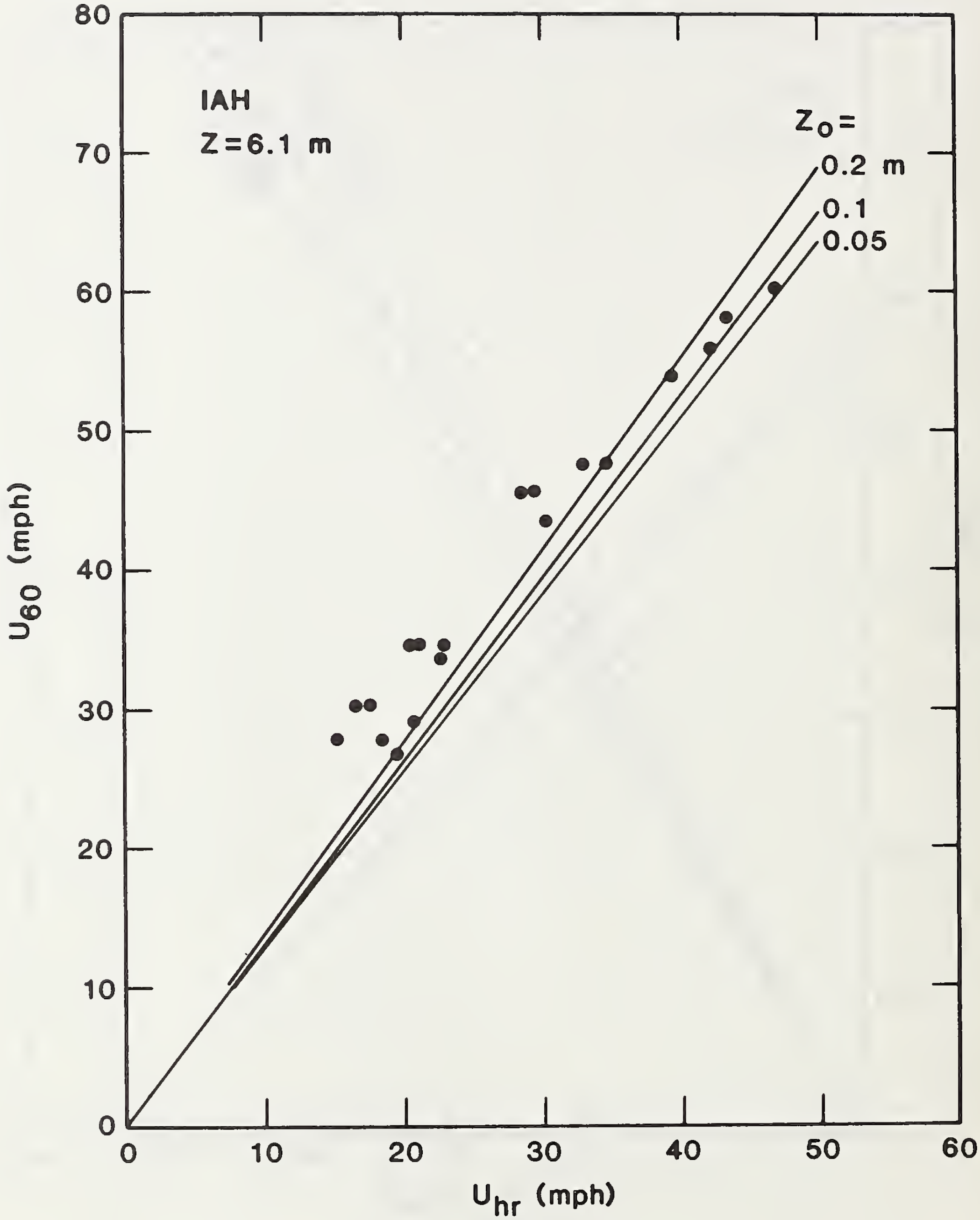

Figure 5. U_{60} vs U_{hr} at IAH

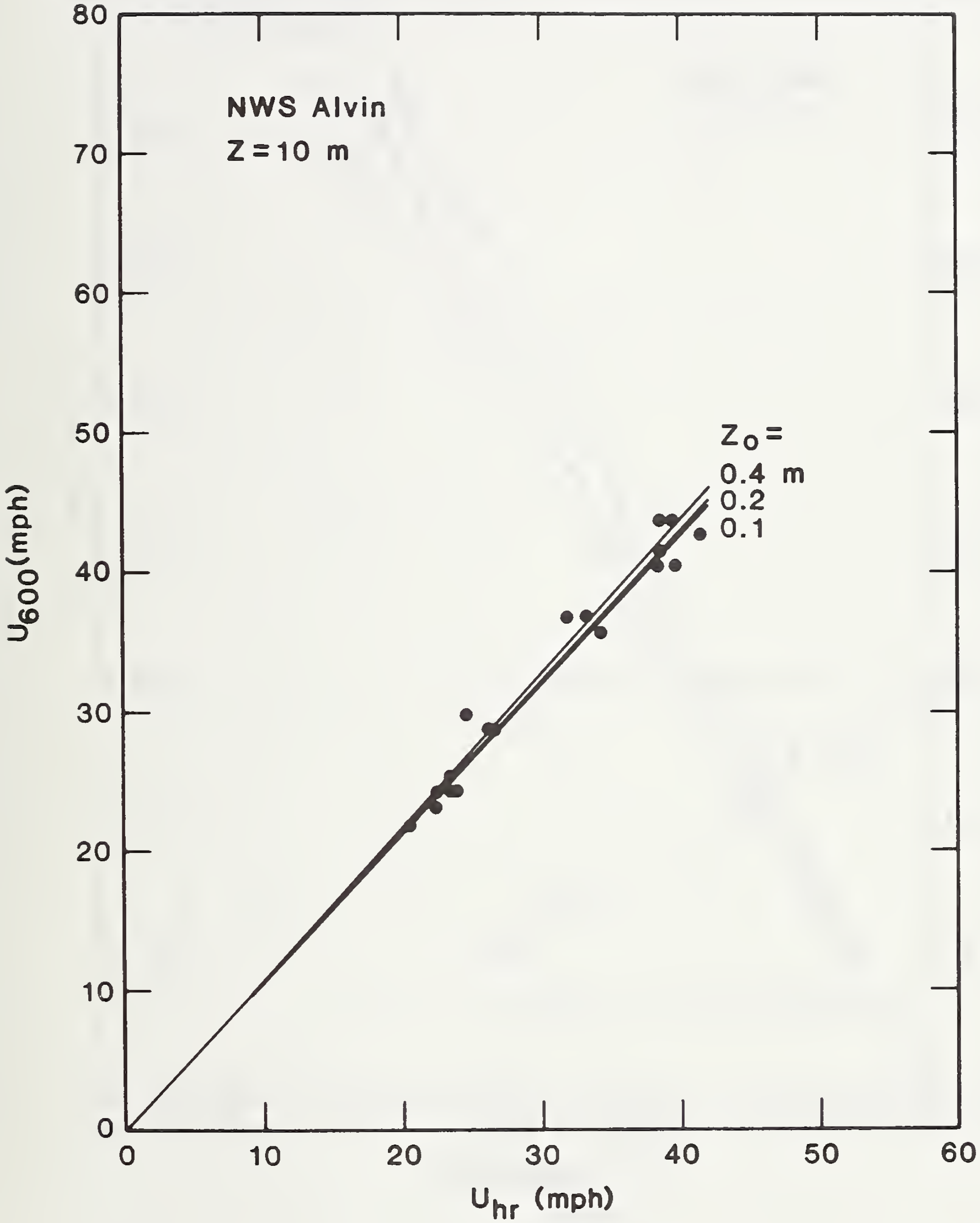

Figure 6. U_{600} vs U_{hr} at NWS Alvin

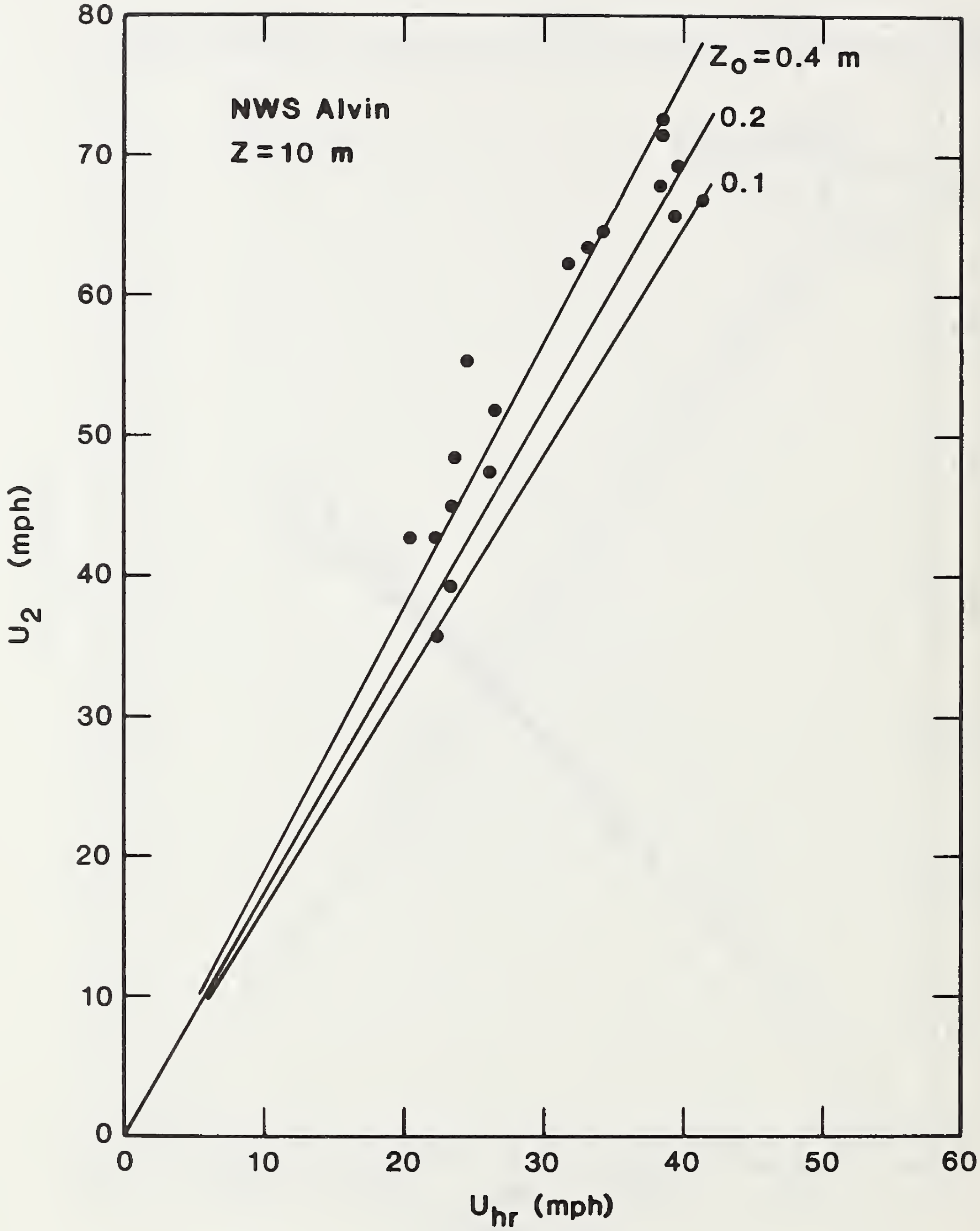

Figure 7. U_2 vs U_{hr} at NWS Alvin

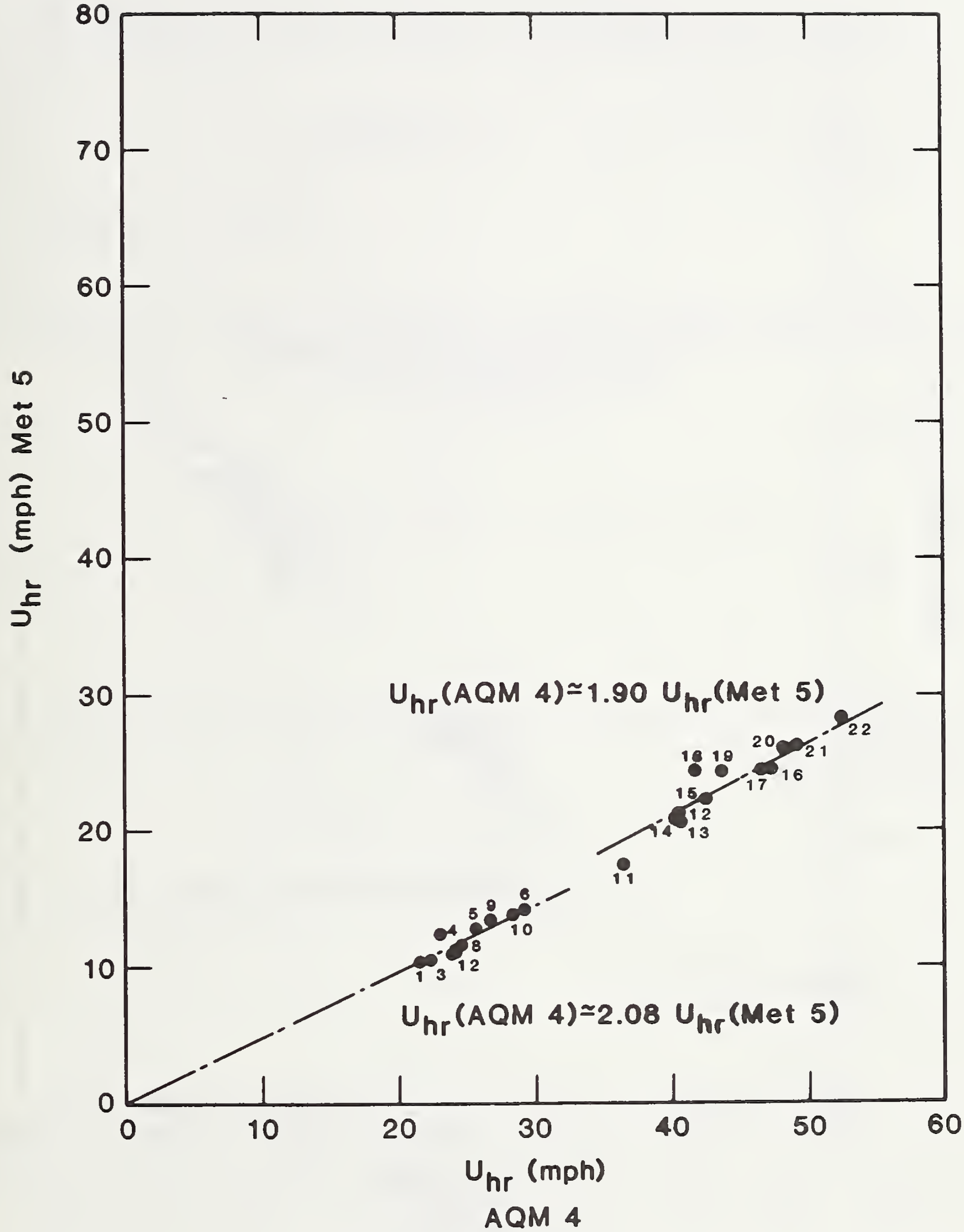

Figure 8. U_{hr} (Met 5, 10 m) vs U_{hr} (AQM 4)

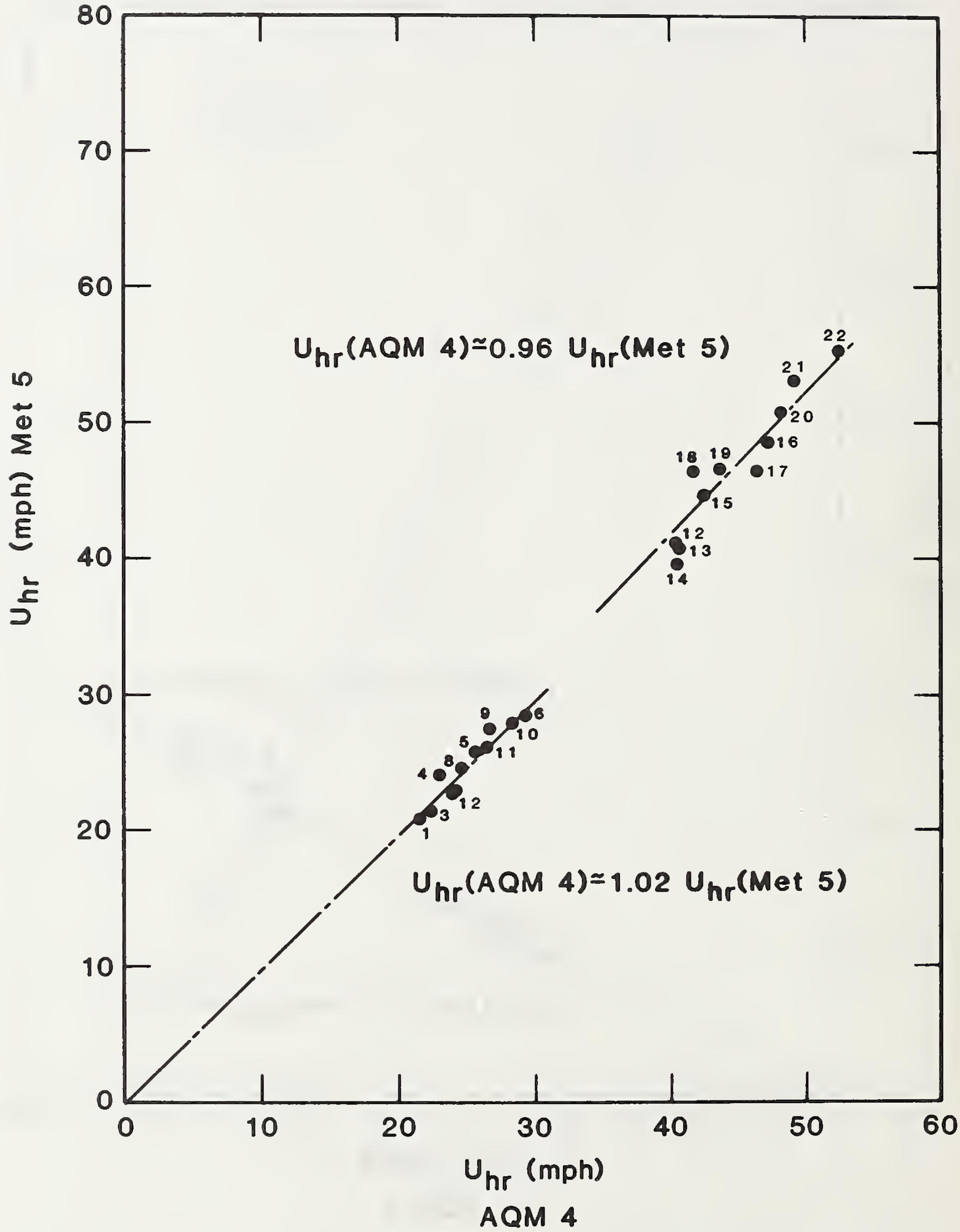

Figure 9. U_{hr} (Met 5, 90 m) vs U_{hr} (AQM 4)

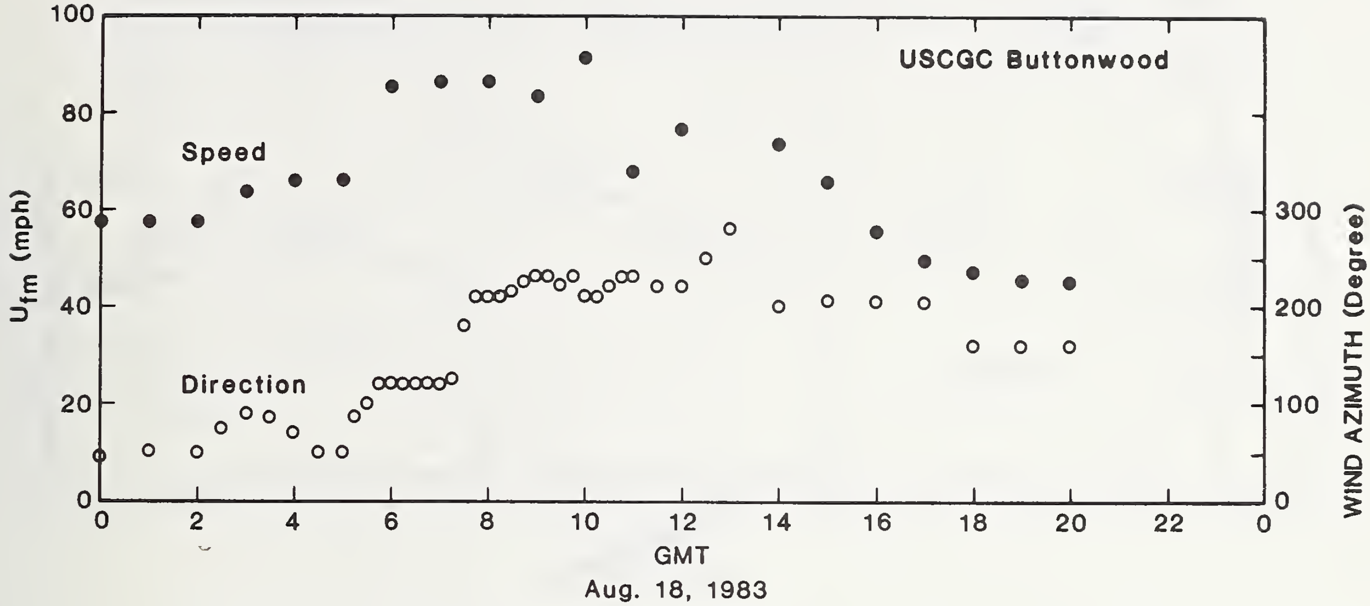

Figure 10. U_{fm} at USCGC Buttonwood

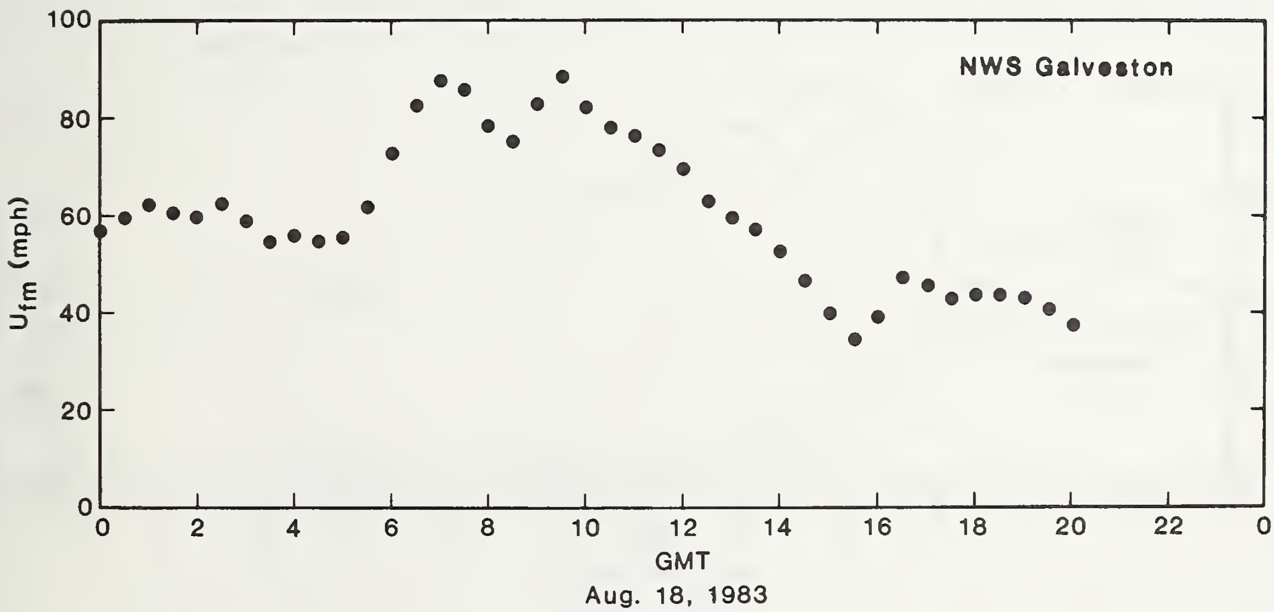

Figure 11. U_{fm} at NWS Galveston

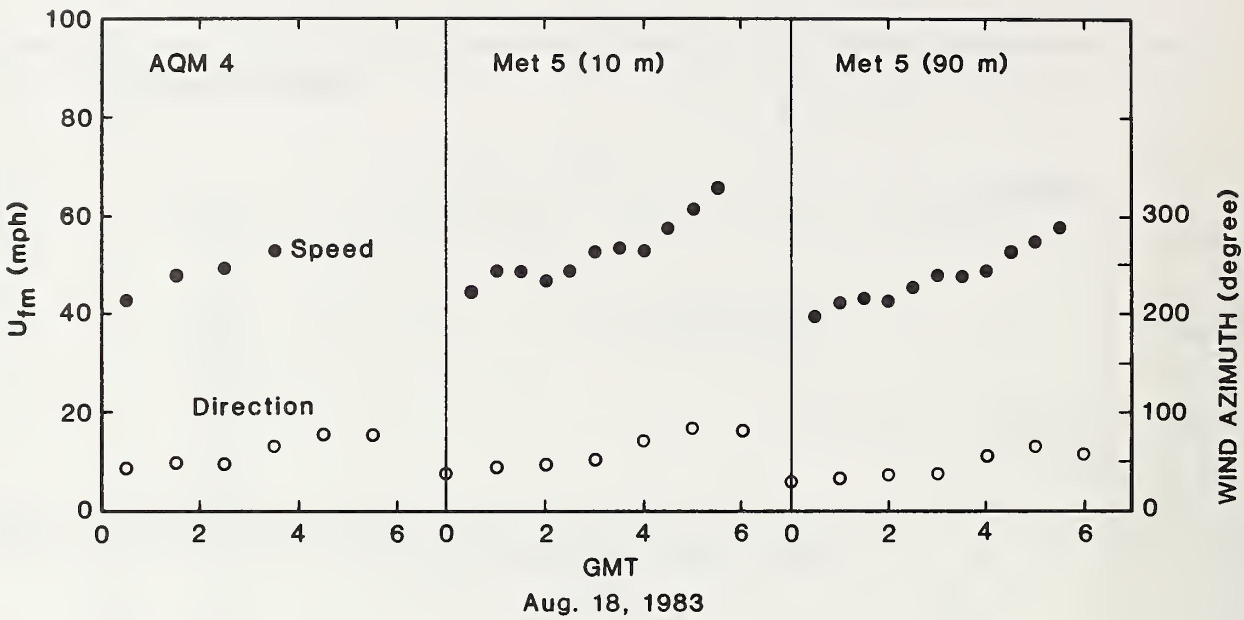

Figure 12. U_{fm} at TCAAMN AQM 4 and Met 5

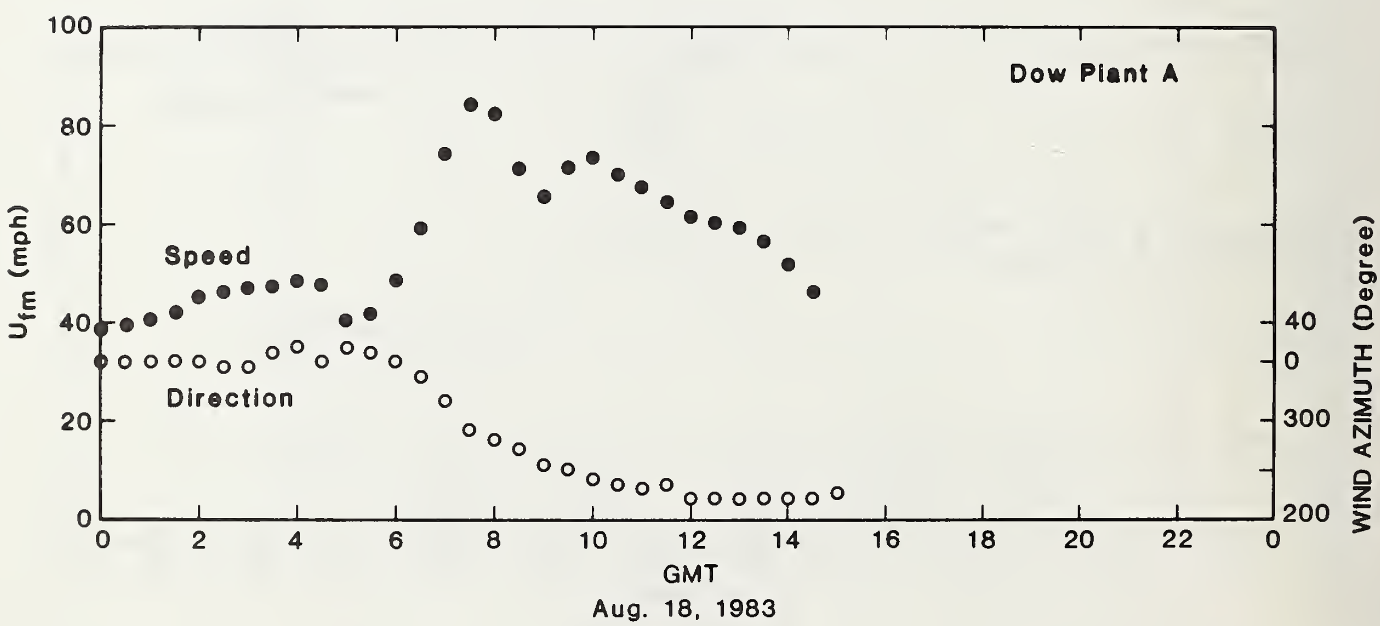

Figure 13. U_{fm} at Dow Plant A

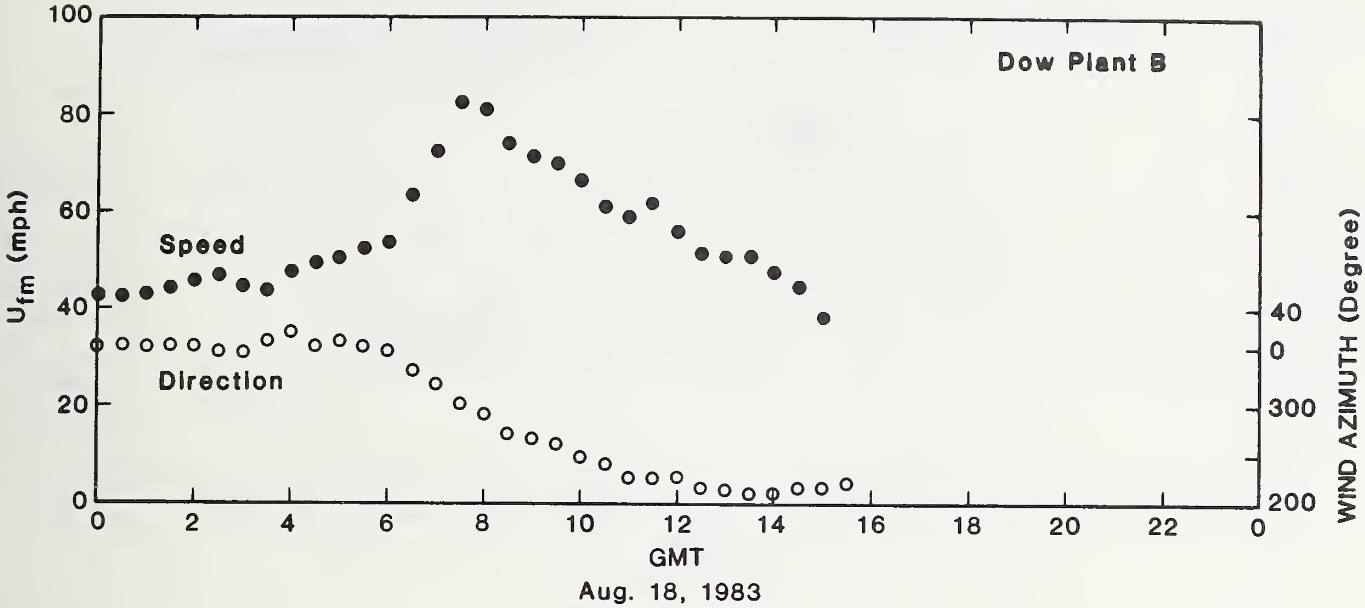

Figure 14. U_{fm} at Dow Plant B

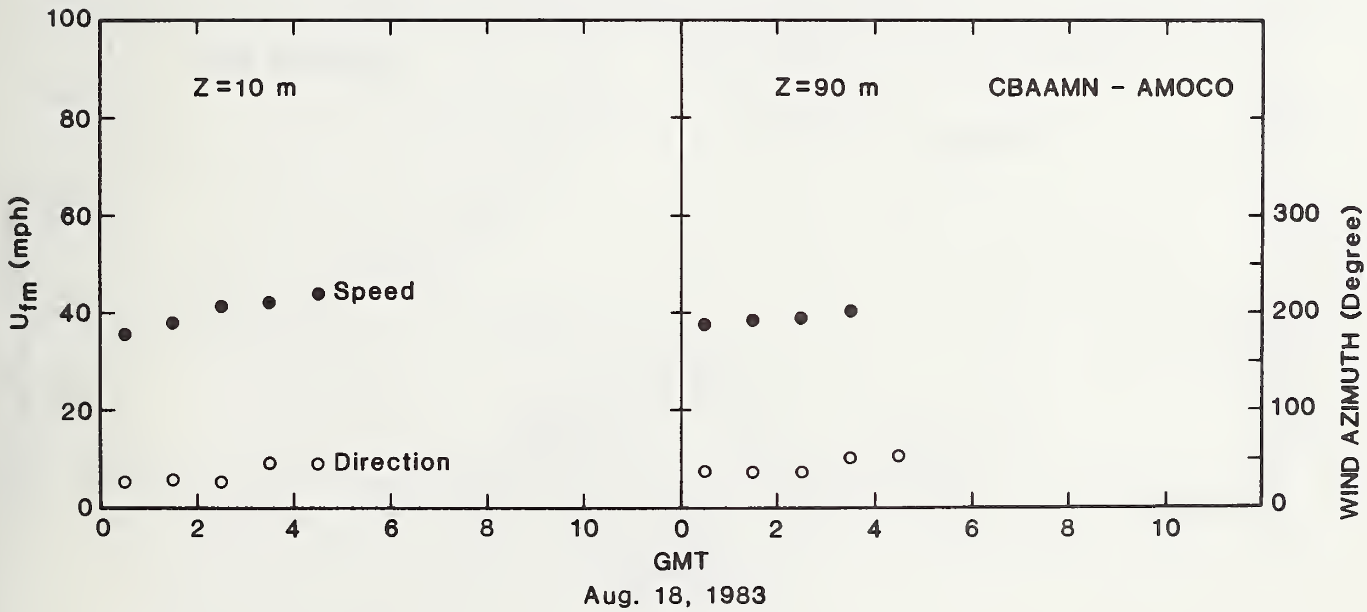

Figure 15. U_{fm} at CBAAMN-Amoco

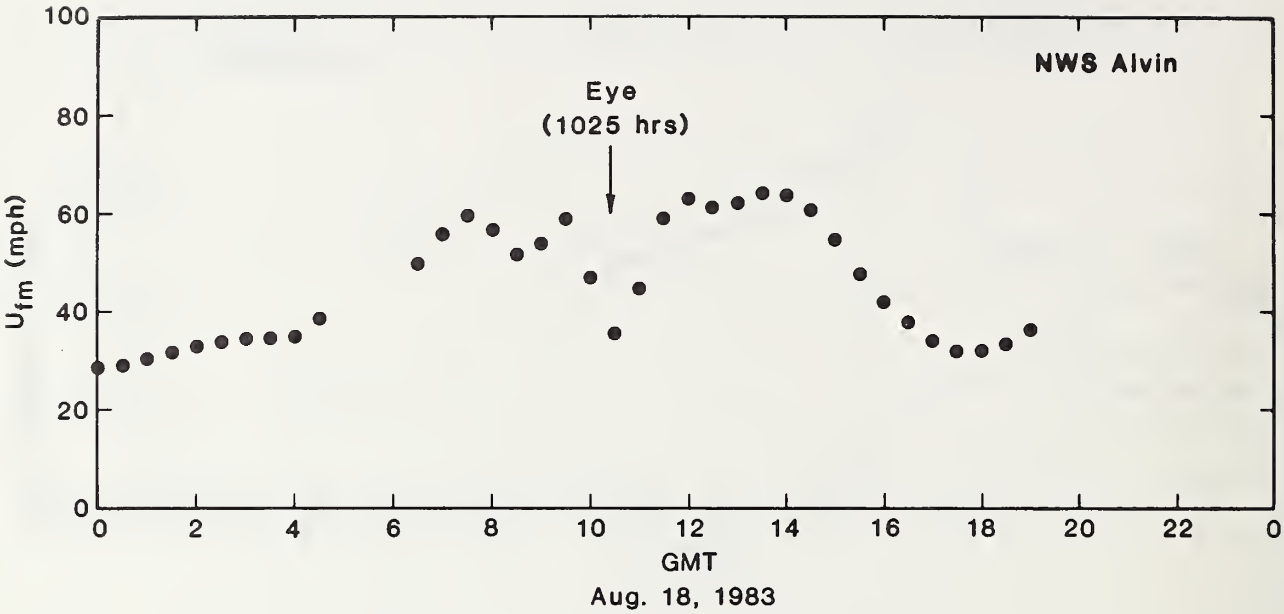

Figure 16. U_{fm} at NWS Alvin

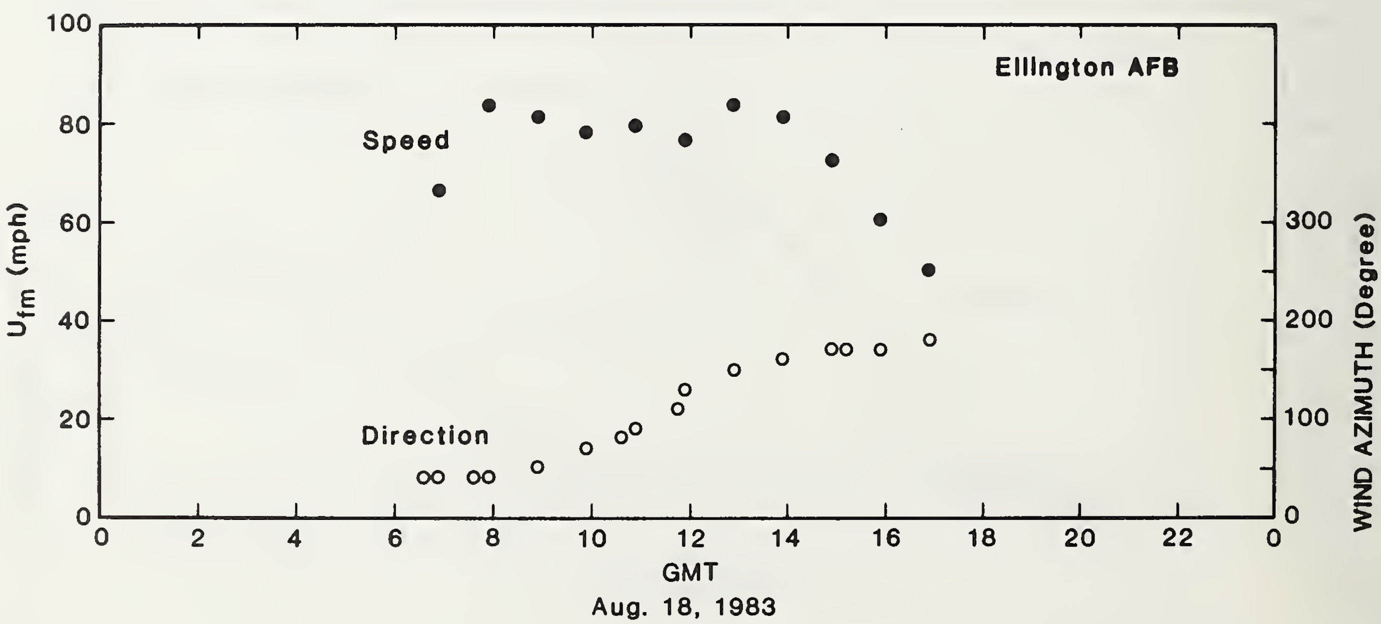

Figure 17. U_{fm} at Ellington AFB

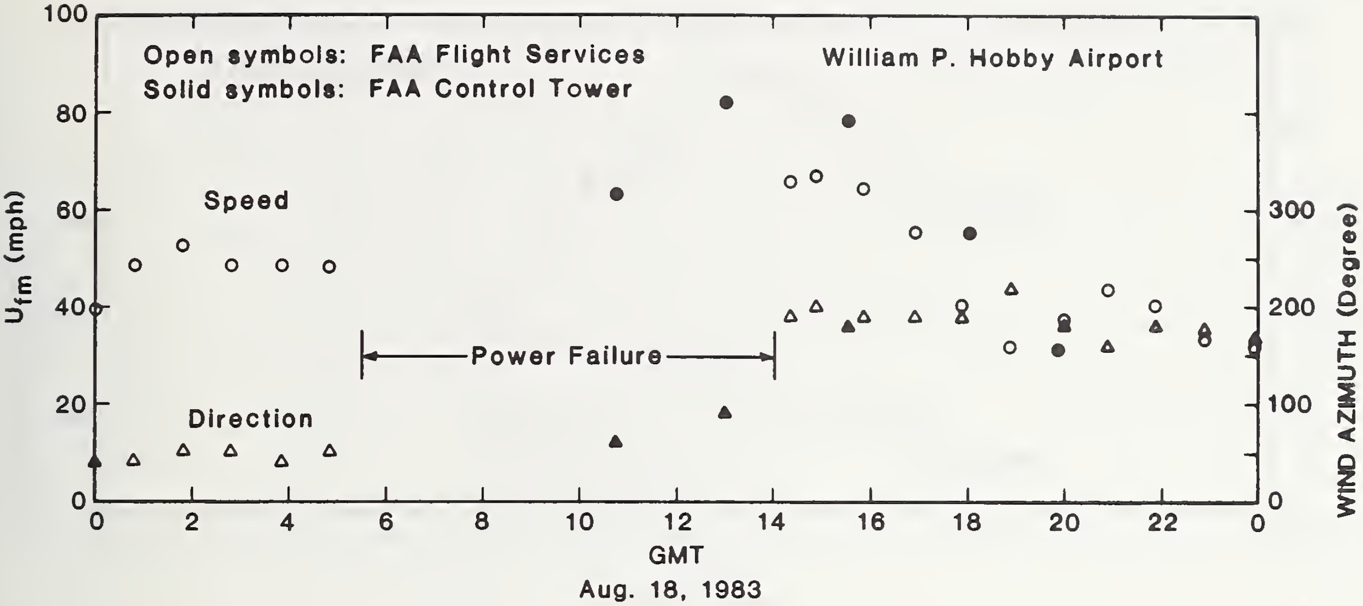

Figure 18. U_{fm} at William P. Hobby Airport

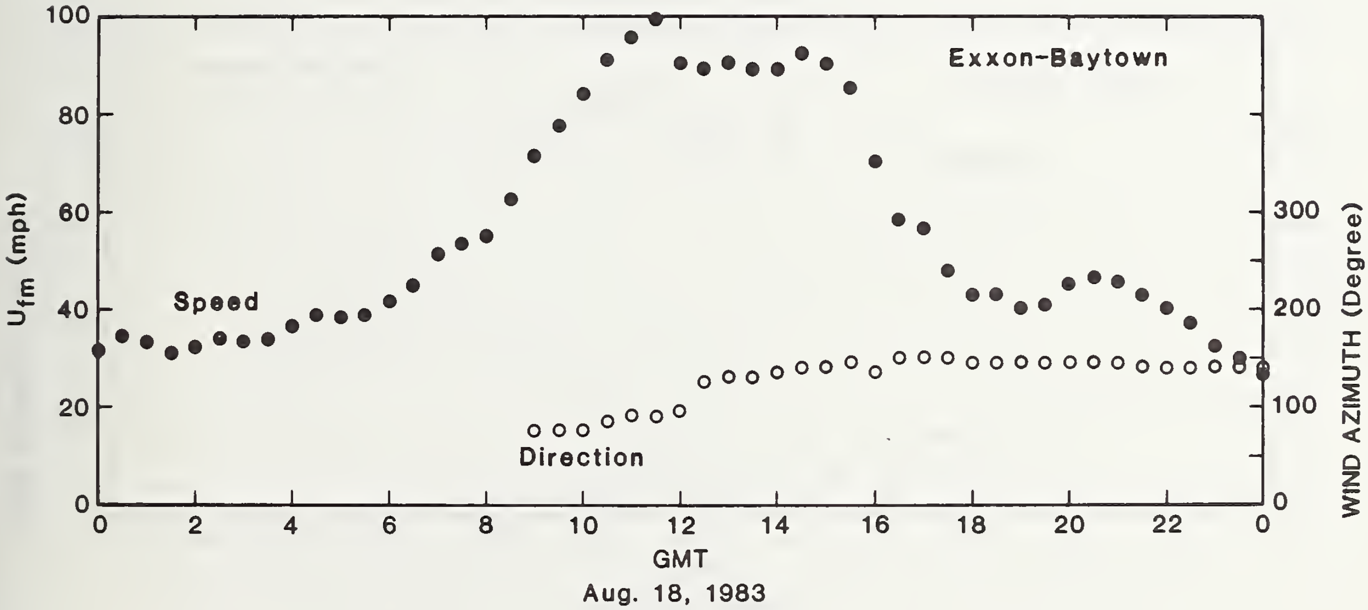

Figure 19. U_{fm} at Exxon-Baytown

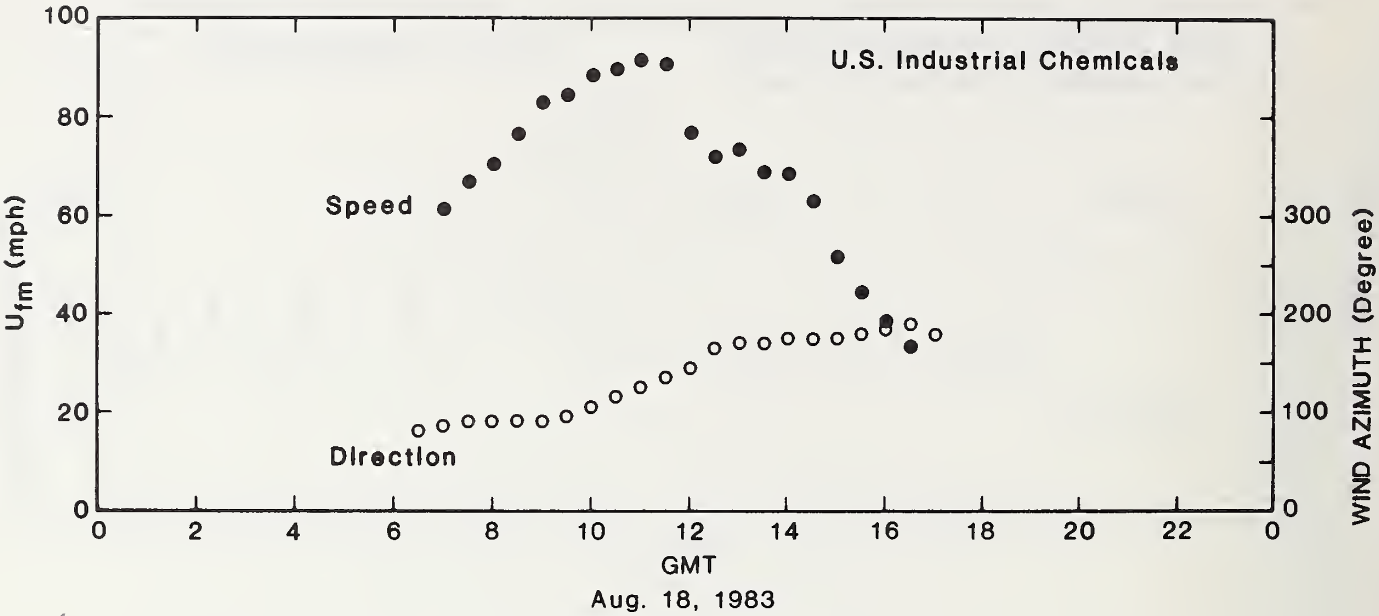

Figure 20. U_{fm} at U.S. Industrial Chemicals

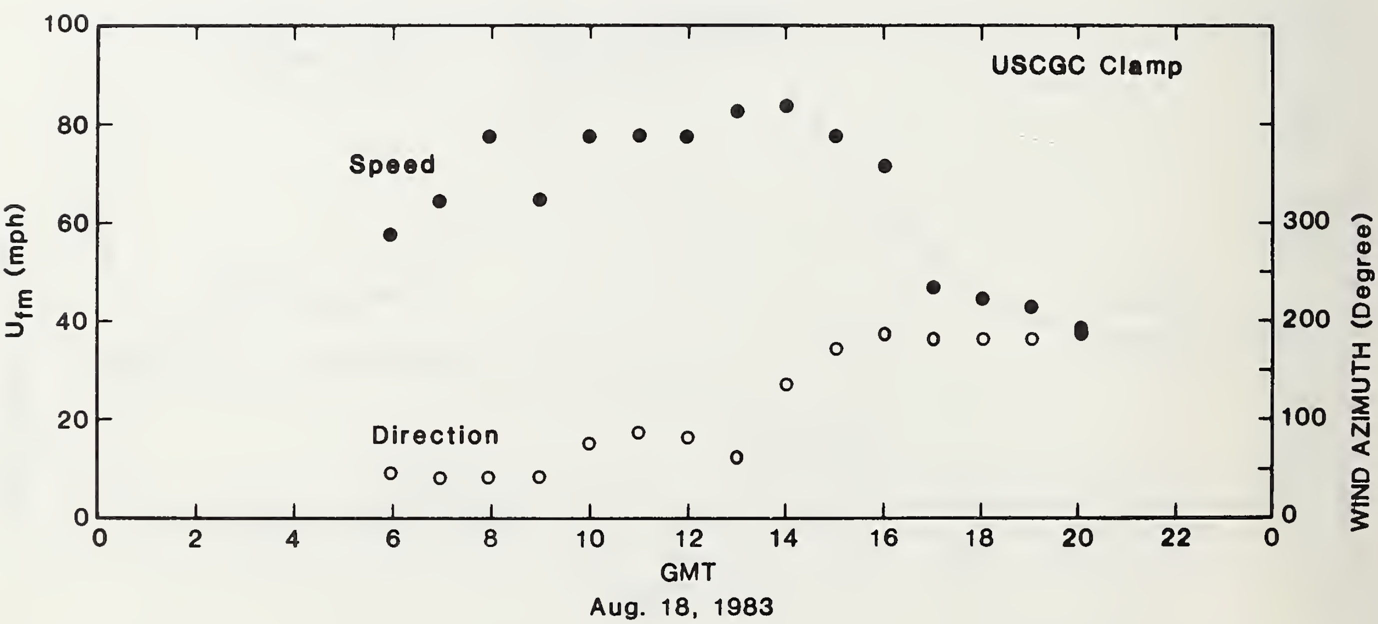

Figure 21. U_{fm} at USCGC Clamp

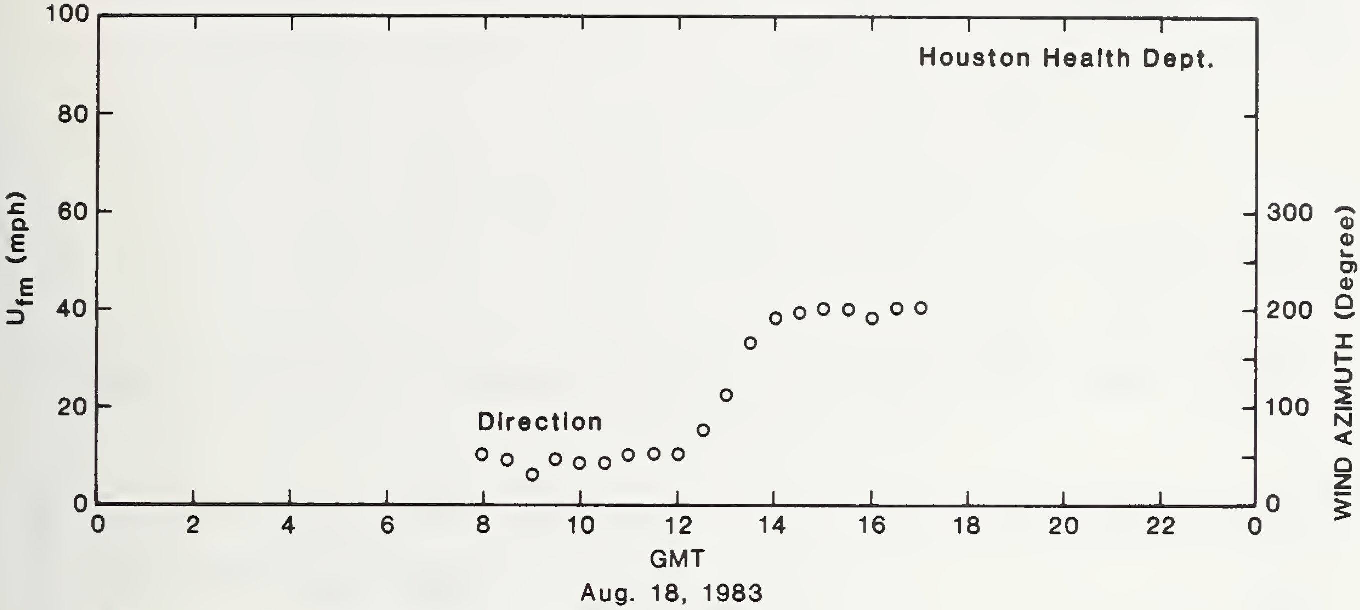

Figure 22. U_{fm} at Houston Health Department

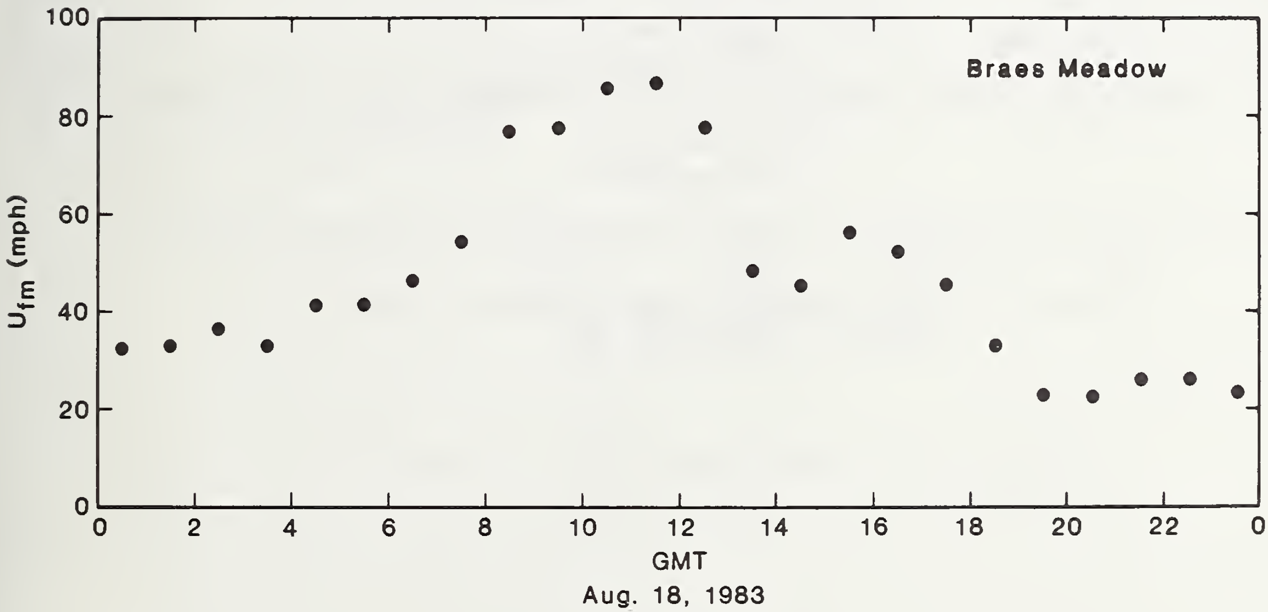

Figure 23. U_{fm} at Braes Meadow

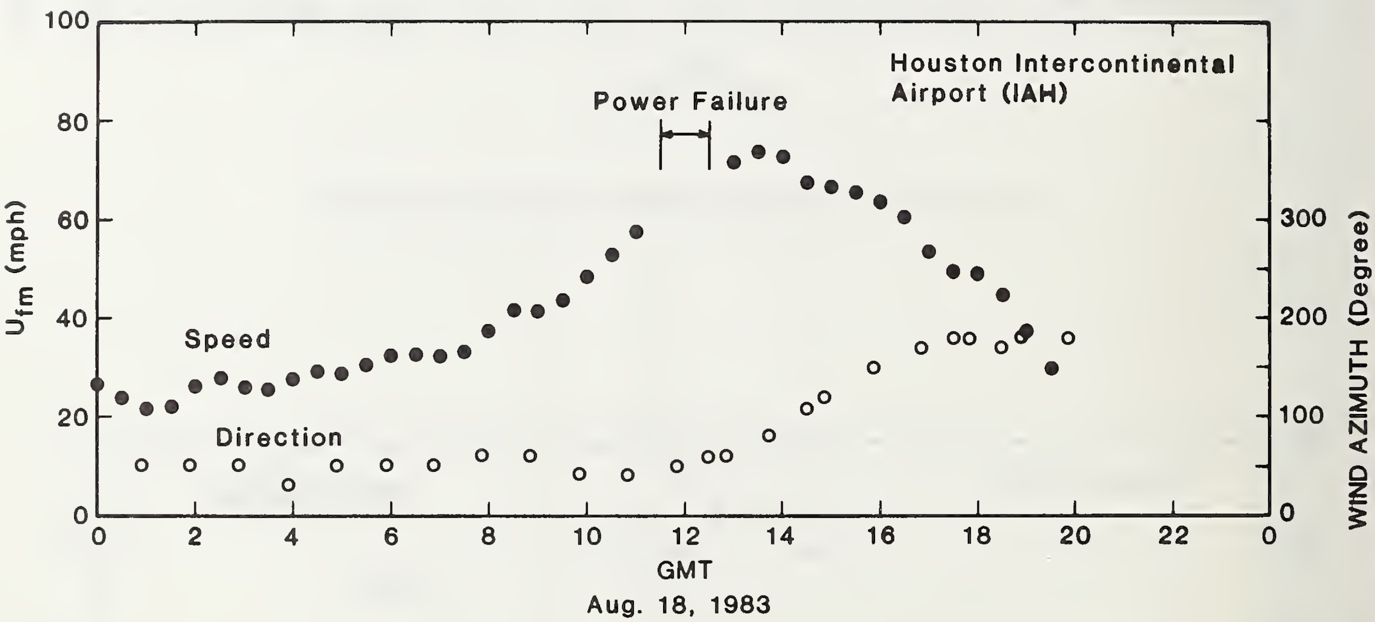

Figure 24. U_{fm} at Houston Intercontinental Airport (IAH)

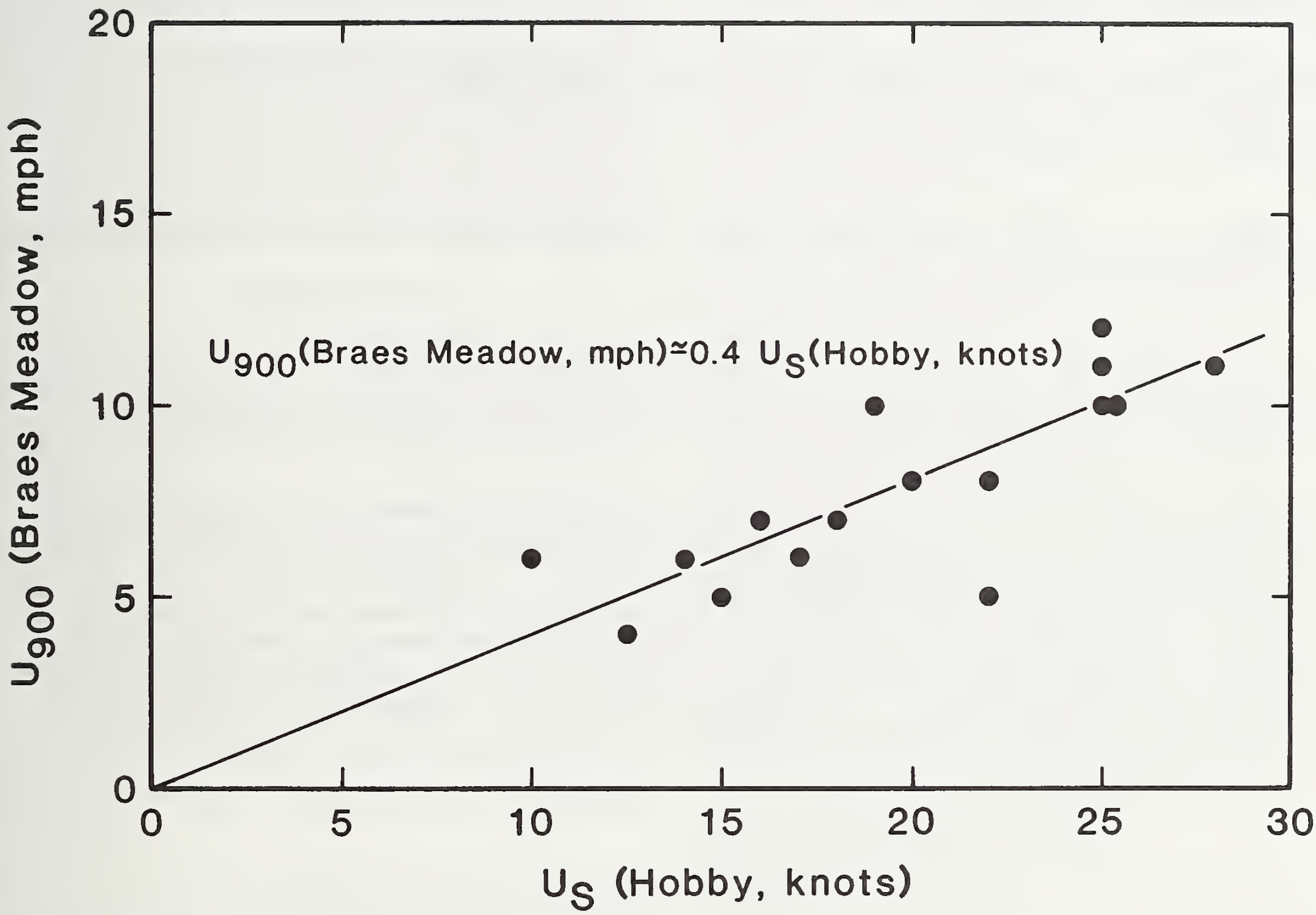

Figure 25. U_{900} (Braes Meadow) vs U_s (Hobby)

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U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS TN 1197	2. Performing Organ. Report No.	3. Publication Date June 1984

4. TITLE AND SUBTITLE

Fastest-Mile Wind Speeds in Hurricane Alicia

5. AUTHOR(S)

Richard D. Marshall

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
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7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

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Surface wind speeds recorded during the passage of Hurricane Alicia through the Galveston-Houston area on August 18, 1983, are used to estimate the fastest-mile wind speeds at 10 m above ground in open terrain. The paper describes the relationships between wind speeds for various averaging times and the boundary-layer representations used in the transformation to fastest-mile speeds. These speeds are compared with wind speeds recommended for the design of buildings and other permanent structures. Errors inherent in the original wind speed records and in the transformations are estimated.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

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